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OUT-OF-CORE SIMPLIFICATION WITH APPEARANCE PRESERVATION FOR COMPUTER GAME APPLICATIONS

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Abstract

Drastic growth in computer simulations' complexity and 3D scanning technology has boosted the size of geometry data sets. Before this, conventional (in-core) simplification techniques are sufficient in data reduction to accelerate graphics rendering. However, powerful graphics workstation also unable to load or even generates the smooth rendering of these extremely large data. In this thesis, out-of-core simplification algorithm is introduced to overcome the limitation of conventional technique. Meanwhile, preservation on surface attributes such as normals, colors and textures, which essential to bring out the beauty of 3D object, are also discussed. The first process is to convert the input data into a memory efficient format. Next, datasets are organized in an octree structure and later partitioned meshes are kept in secondary memory (hard disk). Subsequently, submeshes are simplified using a new variation of vertex clustering technique. In order to maintain the surface attributes, a proposed vertex clustering technique that collapses all triangles in every leaf node using the generalized quadric error metrics is introduced. Unlike any other vertex clustering methods, the knowledge of neighbourhood between nodes is unnecessary and the node simplification is performed independently. This simplification is executed recursively until a desired levels of detail is achieved. During run-time, the visible mesh is rendered based on the distance criterion by extracting the required data from the previously generated octree structure. The evaluated experiments show that the simplification is greatly controlled by octree's subdivision level and end node size. The finer the octree, thus the finer mesh will be generated. Overall, the proposed algorithm is capable in simplifying large datasets with pleasant quality and relatively fast. The system is run efficiently on low cost personal computer with small memory footprint.

Abstrak

Perkembangan drastik dalam simulasi komputer dan teknologi pengimbasan 3D telah meningkatkan saiz data geometri. Sebelum ini, teknik simplifikasi tradisional (*in-core*) mampu mengurangkan saiz data untuk mempercepatkan visualisasi grafik. Walau bagaimanapun, stesen kerja grafik yang berspesifikasi tinggi juga tidak mampu memuat data yang terlalu besar ini apatah lagi menjana visualisasi yang licin. Dalam thesis ini, algoritma simplifikasi *out-of-core* telah diperkenalkan untuk mengatasi kekurangan teknik tradisional. Sementara ini, pengekalan ciri-ciri permukaaan seperti normal, warna dan tekstur yang menunjukkan kecantikan objek 3D telah dibincangkan. Proses pertama ialah menukarkan data input kepada format yang ramah memori. Kemudian, data disusun dalam struktur octree dan data yang siap dibahagikan disimpan dalam memori sekunder (cakera keras). Selepas ini, permukaan bagi setiap nod diringkaskan dengan teknik pengumpulan verteks. Untuk mengekalkan attribut-attribut permukaan, teknik pengumpulan vertex yang menggantikan segitiga-segitiga dalam setiap nod dengan menggunakan kaedah "generalized quadric error metrics" dicadangkan. Berbeza dengan teknik-teknik lain, pengetahuan antara nod jiran tidak diperlukan dan simplifikasi nod dilakukan secara individu. Proses simplifikasi ini dijalankan secara rekursif sehingga bilangan resolusi yang dikehendaki dicapai. Semasa perlaksaan sistem, permukaan yang boleh dinampak divisualisasikan berdasarkan aspek jarak dengan mengekstrak data berkenaan dari struktur octree yang dihasilkan. Eksperimen yang dianalisa menunjukkan bahawa simplifikasi banyak dikawal oleh aras pembahagian octree dan saiz nod akhir. Semakin banyak octree dibahagikan, semakin tinggi resolusi permukaan yang dihasilkan. Secara keseluruhan, algoritma cadangan adalah berpotensi dalam simplifikasi data besar dengan kualiti yang memuaskan dan agak cepat. Sistem ini telah dilaksanakan secara effektif pada komputer berkos rendah dengan penggunaan memori yang kecil.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A 3D interactive graphics application is an extremely computational demanding paradigm, requiring the simulation and display of a virtual environment at interactive frame rates. It is significant in real time game environment. Even with the use of powerful graphics workstations, a moderately complex virtual environment can involve a vast amount of computation, inducing a noticeable lag into the system. This lag can detrimentally affect the visual effect and may therefore severely compromise the diffusion of the quality of graphics application.

Therefore, a lot of techniques have been proposed to overcome the delay of the display. It includes motion prediction, fixed update rate, visibility culling, frameless rendering, Galilean antialiasing, level of detail, world subdivision or even employing parallelism. Researches have been done and recovered that the fixed update rates and level of detail technique are the only solutions which enable the application program balances the load of the system in real-time (Reddy, 1997). Of these solutions, concentration is focused on the notion of level of detail.

Since the mid nineteen-seventies, programmers have used Level of Detail (LOD) management to improve the performance and quality of their graphics systems. The LOD approach involves maintaining a set of representations of each polygonal object, each with varying levels of triangle resolution. During the

execution of the animation, object deemed to be less important is displayed with a low-resolution representation. Where as object of higher importance is displayed with higher level of triangle resolution.

The drastic growth in scanning technology and high realism computer simulation complexity has lead to the increase of dataset size. Only super computer or powerful graphics workstation are capable to handle these massive datasets. For this reason, problem of dealing with meshes that are apparently larger than the available main memory exists. Data, which has hundreds, million of polygons are impossible to fit in any available main memory in desktop personal computer. Because of this memory shortage, conventional simplification methods, which typically require reading and storing the entire model in main memory, cannot be used anymore. Hence, out-of-core approaches are gaining its attention widely.

As commonly known, graphics applications always desire high realism scene yet smooth scene rendering. Smooth rendering can be achieved by reducing the number of polygons to a suitable level of detail using the simplification technique. It saves milliseconds of execution time that help to improve performance. However, in order to obtain a nice simplified mesh, surface attributes other than geometry information are essential to be preserved as well. Eye catching surface appearance certainly will increase the beauty of the scene effectively.

1.2 Background Research

Traditionally, polygonal models have been used in computer graphics extensively. Till this moment, large variety of applications is using this fundamental primitive to represent three dimensional objects. Besides, many graphics hardware and software rendering systems support this data structure. In addition, all virtual environment systems employ polygon renderers as their graphics engine.

In reality, many computational demanding systems desire smooth rendering of these polygonal meshes. To optimize the speed and quality of graphics rendering,

level of details has been used widely to reduce the complexity of the polygonal mesh using level of detail technique. In short, a process which takes an original polygon description of a three dimensional object and creates another such description, retaining the general shape and appearance of the original model, but containing fewer polygons.

Recent advances in scanning technology, simulation complexity and storage capacity have lead to an explosion in the availability and complexity of polygonal models, which often consist of millions of polygons. Because of the memory shortage in dealing with meshes that are significantly larger than available main memory, conventional methods, which typically require reading and storing the entire model in main memory during simplification process, cannot solve the dilemma anymore. Thus, out-of-core approaches are introduced consequently.

Out-of-core algorithms are also known as external algorithms or secondary memory algorithms. Out-of-core algorithms keep the bulk of the data on disk, and keep in main memory (or so called in-core) only the part of the data that's being processed. Lindstrom (Lindstrom, 2000a) is the pioneer in out-of-core simplification field. He created a simplification method; called OoCS which is independent of input mesh size. However, the output size of the mesh must be smaller than the available main memory. Later on, other researchers carried out similar approaches.

Especially in out-of-core simplification, a large number of research have been done on level of detail's construction and management for use in interactive graphics applications, mostly in medical visualization, flight simulators, terrain visualization systems, computer aided design and computer games. For instance, simplification is used broadly in medical and scientific visualization. It always involves a lot of processing on high resolution three dimensional data sets. The data is mainly produced by those high technology scanners, such as CT or MRI scanners. The simplification process may need to extract volumetric data at different density levels. If the accuracy is not that critical, one may only process on its isosurfaces. Anyhow, these data simplification require a lot of processing time and it is mainly run daily on supercomputers worldwide.

Graphics applications, which demand high accuracy in simplification development is critical. It is essential to maintain the high quality and good frame rates at the same time. For example, medical visualization and terrain visualization is crucial in maintaining a good visual fidelity. Anyway, in many real time systems, the quality of data visualization has to be degraded in order to retain superior rendering time. For instance, an excellent frame rate is vital in game environment without doubt. Thus, the quality of simplified model has to be sacrificed sometimes.

Rendering the large models at interactive frame rates is essential in many areas, includes entertainment, training, simulation and urban planning. Out-of-core techniques are required to display large models at interactive frame rates using low memory machines. Hence, it needs new solution or further improvement such as prefetching, geomorphing, appearance preservation, parallelization, visibility pre-computing, geometry caching, image-based rendering, and etc.

To avoid the last minute data fetching when needed, prefetching, visibility pre-computing and geometry caching are imperative. Although the changes from frame to frame are regularly small, however, they are occasionally large, so, prefetching technique is needed. This technique predicts or speculates which part of the model are likely to become visible in the next few frames then prefetch them from disk ahead of time. Correa *et al*. (2002) showed that prefetching can be based on from-point visibility algorithms. Visibility can be pre-computed using from-region visibility or from-point visibility. Whilst geometry caching exploits the coherence between frames, thus keeping geometry cache in main memory and update the cache as the viewing parameters changes.

Above and beyond, parallelization and image-based rendering enhance the frame rates as well. Parallelization (Correa *et al*., 2002) uses a few processors to run different tasks at the same time. Or, it can make use of multithreading concept in a single-processor machine too. On the other hand, image-based rendering techniques (Wilson and Monacha, 2003) such as texture-mapped impostors can be used to accelerate the rendering process. These texture-mapped impostors are generated either in a preprocessing step or at runtime (but not every frame). These techniques are suitable for outdoor models.

The geomorphing and surface preserving are potential in pleasant scene rendering. An unfortunate side effect of rendering with dynamic levels of detail is the sudden visual ‘pop’ that occurs when triangles are inserted or removed from the mesh. Geomorphing allows smooth transitions between the approximations (Levenberg, 20002; Erikson, 2000; Hoppe, 1998a). In virtual environments or three dimensional game engines, the surface attributes play an important role to make the object looks attractive. Therefore, these surface attributes like colors and textures should be maintained after simplification process.

1.3 Motivations

Why do we care about visualization of large datasets? Due to the advances in scanning technology and complexity of computer simulation, the size of the datasets grows rapidly these years. The data is vital because it has application in many areas, such as computer design and engineering, visualization of medical data, modeling and simulation of weapons, exploration of oil and gas, virtual training and many more.

These massive data can only be rendered on high end computer system. If it is needed to run on personal computer, it may be an impossible mission, or even it can, the output is jagged or ungraceful. Therefore, to run it on expensive high end graphics machine, it is very cost ineffective and not user friendly. There is a need to display the data in low cost PC with high quality output.

Surface attributes, for example, normal, curvature, color and texture values are important to make the rendered objects looks attractive. It can increase the realism of a virtual environment. It shows the details of an object, such as its illumination, lighting effect and material attributes. Without it, the rendered scene will become dull and bored.

1.4 Problem Statement

The datasets are getting enormous in size. However, even the well implemented in-core methods no more able to simplify these massive datasets. This is mainly because in-core approach loads the whole full resolution mesh into main memory during simplification process. Besides, we cannot keep relying on high end graphics machine as it is expensive and not everyone has the chance to use it. Therefore, when the datasets bigger than the main memory, the datasets cannot be simplified.

Geometry aspects like vertex position always retained after simplification process whether in in-core simplification or out-of-core simplification. However, work in preserving the surface appearance, e.g. surface normal, curvature and color or even texture attributes in the original mesh is not common in out-of-core simplification approach. The lost surface attributes will greatly reduce the realism of virtual environment.

1.5 Purpose

To render the massive datasets in 3D real-time environment and preserve its surface appearance during simplification process using commodity personal computer.

1.6 Objectives

1. To develop an out-of-core simplification technique.
2. To preserve the surface attributes on the out-of-core model based on error metrics.

1.7 Research Scope

a) Only triangular polygonal mesh is considered, other data representation is not investigated here.

b) The simplification is for only static polygonal objects, dynamic object is not covered here.

c) Only vertex positions, normals, colors and texture coordinates are preserved after simplification process.

d) Application is run on commodity personal computer. Commodity in this content means low cost PC with not more than 2GB RAM and not any kind of SGI machine.

e) Graphics card of the PC is assumed capable in handling real time rendering.

f) Only simple level of detail management system is applied by using distance criterion.

g) Secondary memory used here is the hard disk, other secondary memory devices are not investigated its cons and pros.

h) The size of the datasets mustn't larger than the size of secondary memory owned by the machine.

i) No other enhancement techniques such as geomorphing, prefetching, caching, parallelization and no disk usage reduction are investigated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Mesh simplification reduces storage requirements and computational complexity. For these reason, the scene rendering frame rate also becomes faster. In order to make the simplification suits into real time application, there are a few processes to go through. First, determine the level of detail framework to be used. Each LOD framework has its cons and pros. It is chosen based on application needs. Next, work on level of detail management to choose suitable or appropriate selection criteria. Then, to generate each level of detail for an object, simplification method is taken into account. For sure, metrics for simplification and quality evaluation is required as well.

The large datasets cannot be simplified using the ordinary in-core simplification methods as discussed before. It is inadequate. The large dataset simplification needs more mechanisms to make it run able in real time on low cost personal computer. First of all, the large dataset need to be loaded into system using external memory algorithm. Then, then data shall be organized into suitable structure, which facilitate and accelerate the real time rendering. Last but not least, it has to be simplified using out-of-core simplification algorithm.

Here, the essential algorithms in making out-of-core simplification success in graphics application are discussed in a few sections. In Section 2.2, the level of

detail framework is discussed. Following it, Section 2.3 shows the level of detail management implemented so far. Then, researches that had been done in simplifying object are explained in Section 2.4. Next, the error metrics for simplification and evaluation are revealed in Section 2.5. Then, external memory management (Section 2.6) and out-of-core approaches (Section 2.7) are carried out. Later on, several comparisons carried out to differentiate all of the existing techniques (Section 2.8). Next, the appearance preservation is discussed in Section 2.9. Last but not least, this work is concluded in last section.

2.2 Level of Detail Framework

Currently, there are three different kinds of LOD framework, which are discrete LOD, continuous LOD and view-dependent LOD. Discrete LOD is the traditional approach, which is being used since 1976. Continuous LOD was developed in year 1996, while view-dependent LOD was created in the following year.

2.2.1 Discrete Level of Detail

Discrete level of detail creates several discrete versions of the object during a pre-process time. During run-time, it picks the most appropriate level of detail to represent the object according to some particular selection criteria. Many works select the appropriate level of detail using the distance aspect (Funkhouser and Sequin, 1993; Garland and Heckbert, 1997; Erikson *et al*., 2001). Since levels of detail are created offline at fixed resolutions, so it is called discrete level of detail or static polygonal simplification.

Discrete level of detail has its advantages and disadvantages. The most significant advantage is it is the simplest model to be programmed. Simply, the level of detail creation does not encounter any real-time constraints, as it is computed

offline. It imposes very little overhead during run-time process. Secondly, it fits the modern graphics hardware well. It is easily to compile each level of detail into triangle strips, display list, vertex array and so on. Hence, it may accelerate the rendering process compared to unorganized list of polygons.

Even the implementation of discrete LOD is straightforward, popping artifacts may occur during level of detail switching. Besides, it is unsuitable for large datasets simplification if the whole simplified mesh is loaded during run-time without taking any viewing aspect into consideration.

2.2.2 Continuous Level of Detail

Continuous LOD is a departure from the traditional discrete approach. Discrete LOD creates individual levels of detail in a pre-process. Contrast to this, continuous LOD creates data structure, which enables desired level of detail can be extracted during run time.

Continuous LOD has better fidelity. The level of detail is specified exactly, not chosen from a few pre-created options. Thus objects use no more unnecessary polygons, which free up polygons for other objects. Therefore, it has better resource utilization and leads to better overall fidelity. By using continuous LOD, transition between approximations is smoother (Lindstrom *et al*., 1996; Xia *et al*., 1997; El-Sana and Varshney, 1998). This is because continuous LOD can adjust detail gradually and incrementally, subsequently reduces visual pops. To further eliminate visual pops, geomorphing technique can be applied. Additionally, it supports progressive transmission (Hoppe, 1996). However, it is inappropriate to use it in real-time massive data simplification.

2.2.3 View-Dependent Level of Detail

View-dependent LOD uses current view parameters to select best representation for the current view. A single object may span several levels of detail. It is a selective refinement of continuous LOD. It shows nearby portions of object at higher resolution than distant portions (Hoppe, 1997; Luebke and Erikson, 1997; El-Sana and Varshney, 1999, Lindstrom, 2003b). Silhouette regions of an object may appear at a higher resolution than interior regions. View-dependent LOD can also take into account the user peripheral vision.

View-dependent LOD has better granularity than continuous LOD do. This is because it allocates polygons where they are most needed, within as well as among objects. For instance, one may consider a situation where only a part of object is near to viewer whilst the rest are not. If discrete LOD or continuous LOD is used, one may either use the high detail mesh or low detail mesh. It is rather unpractical as using the high detail mesh creates the unacceptable frame rates and the low detail mesh creates terrible fidelity.

The obvious disadvantage of view-dependent LOD is the increased loading time in choosing and extracting the appropriate LOD. If the system is run in real-time or CPU bound, this extra work will decrease the frame rate and subsequently induce lag artifacts.

2.3 Level of Detail Management

Level of detail management is an important process to choose the best level of detail for the object representation in different conditions. In deciding the most appropriate level of detail, different criteria have been developed to optimize the level of detail selection.

Traditionally, the system assigns levels of detail in a range of distances (Kemeny, 1993; Vince, 1993, Chrislip and Ehlert Jr., 1995, Carey and Bell, 1997).

Basically a corresponding level of detail is applied based on the object's distance to the user viewpoint. It may create visual 'pop' and does not maintain constant frame rate. The correct switching distance may vary with field of view, resolution and etc. However, it is extremely simple to understand and to implement.

A more sophisticated level of detail management is required to enhance the level of detail selection. Here, other implemented levels of detail selection techniques are encapsulated as below:

a) Size

An object's LOD is based upon its pixel size on the display device. It can overcome the weakness of distance selection criterion (Wernecke, 1993).

b) Eccentricity

An object's LOD is based upon the degree to which it exists in the periphery of the display (Funkhouser and Sequin, 1993; Ohshima *et al*., 1996; Reddy, 1995; Watson *et al*., 1995). It is generally assumed that the user will be looking towards the centre of the display if suitable eye tracking system is absent. Thus, objects are degraded in relation to their displacement from this point.

c) Velocity

An object's LOD is based upon its velocity relative to the user, e.g. its velocity across the display device or the user's retina (Ohshima *et al*., 1996; Funkhouser and Sequin, 1993). Funkhouser and Sequin (1993) acknowledge that the objects moving quickly across the screen appear blurred, or can be seen only for only a short period of time, and hence the user may not be able to see them clearly.

However, different idea comes from Brown *et al.* (2003a), which is visual importance-biased image synthesis animation. He extends the ideas by incorporating temporal changes into the models and techniques developed. This research indicates that motion is a strong attractor of visual attention. It also shows that high correlation of points between viewers when observing

images containing movement. This is probably point to slow moving object but not a fast moving object.

d) Fixed Frame Rate

Distinct from others, fixed frame rate concerns computational optimization rather than perceptual optimization. An object's LOD is modulated in order to achieve a prescribed update rate. The refresh of screen must be in certain speed even sometimes the realism of scene has to be sacrificed.

Time-critical rendering ensures guaranteed frame rates even on scenes with very high complexity (Zach *et al.*, 2002). This presented time-critical rendering approach that combines discrete and continuous LOD selection and demonstrated its benefits in a terrain flyover application. The rendering process of every frame has to meet strict timing constraints to attain the best visual quality with the available rendering time.

e) Human Eyes Limitation

Resolution of element depends upon the depth of field focus of the user's eyes. For example, objects out with the fusional area appear in lower detail. Highest sensitivity to spatial detail at fovea, other area is less sensitive. Another weakness of human eye is saccade. A saccade is a rapid reflex movement of the eye to fixate a target onto the fovea. Human do not appear to perceive detail during saccade.

Change Blindness (Cater *et al.*, 2003), a major side effect of brief visual disruptions, including an eye saccade, a flicker or a blink, where portions of the scene that have changed simultaneously with the visual disruption go unnoticed to the viewer. Without automatic control, attention is controlled entirely by slower, highly-level mechanisms in the visual system, that search the scene, object by object, until attention finally focuses on the object that is changing. Once attention has latched onto the appropriate object, the change is easy to see, but this occurs only after exhaustive serial inspection of the scene.

There are two major influences on human visual attention: bottom-up and top-down processing. Bottom-up processing is the automatic direction of gaze to lively or colourful objects as determined by low-level vision. In contrast, top-down processing is consciously directed attention in the pursuit of predetermined goals or tasks. This technique demonstrated the principle of Inattentional Blindness (Cater, 2002), a major side effect of top-down processing, where portions of the scene that unrelated to the specified task are unnoticed.

f) Environment Conditions

Slacken level of detail thresholds through the use of fog, haze, clouds, smoke, and etc. This is because these effects make the scene blur and hard to perceive the actual detail.

g) Attention-Directed

This concept works out on where the user is likely to be looking at by using models of visual attention. Or, control where the user looks through the dramatic content of your scenes.

Visual attention-based technique allocates polygons to objects in a scene according their visual importance (Brown *et al.*, 2003b). Every object is assigned an object importance value by considering the size, position, motion and luminance of the object. Then, a suitable level of detail will be taken for each object.

h) Shader LOD

Procedural shaders can adjust their detail as well. For example, convert bump map to texture map, texture map or noise function to single color, multi textures to one texture or using BRDF approximations.

2.4 Level of Detail Generation

Automatic generation of various levels of detail is essential. Without this ability, multiresolution of meshes have to be generated manually. Such activity would be a tedious and laborious process. Hence, a variety of level of detail generation techniques has been proposed and generally known (Figure 2.1).

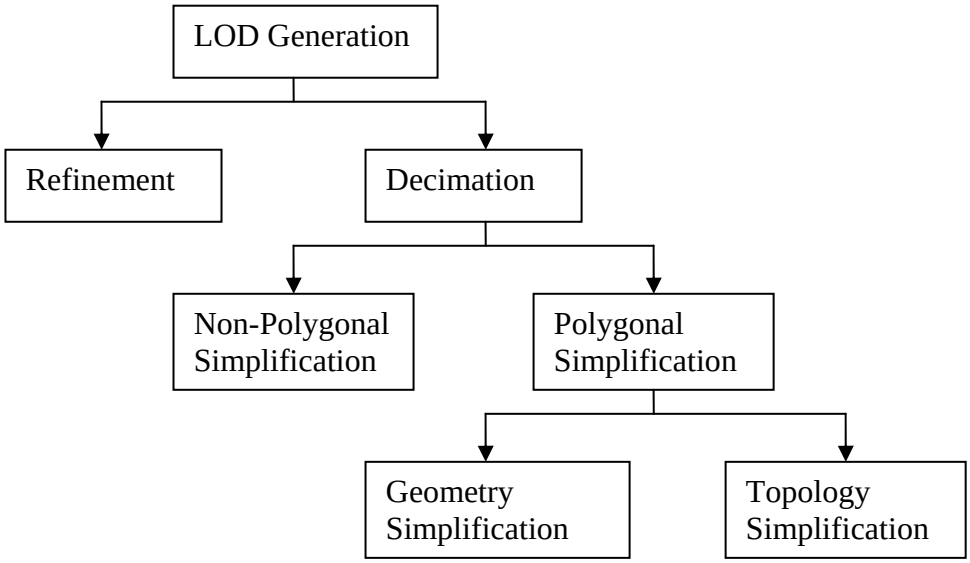


Figure 2.1 Level of detail generation classification

The most widespread methodologies in surface simplification are refinement and decimation. Refinement algorithm begins with an initial coarse approximation and adds details in each step. Essentially the opposition of refinement, decimation algorithm begins with the original surface and iteratively removes details at each step. Both refinement and decimation derive an approximation through a transformation from initial surface. Many algorithms have been developed in both approaches. However, decimation algorithm seems to have a more vital role in memory management.

Decimation simplification can either be polygonal simplification or non-polygonal simplification. Non-polygonal simplification includes parametric spline surface simplification, simplification of volumetric models and also image based simplification. For an example, Alliez and Schmitt (1999) minimize a volume using

the gradient-based optimization algorithm and finite-element interpolation model. Nooruddin and Turk (2003) also use voxel-based method with 3D morphological operators in their simplification. Practically, mostly all virtual environment systems employ polygon renderer as their graphics engine. Therefore, it is common to convert any other model types into polygonal surfaces before rendering. Hence, the polygonal model is ubiquitous. Pragmatically, the focus falls on polygonal model.

Polygon simplification can be categorized into geometry simplification and topology simplification. Geometric simplification reduces the number of geometric primitives such as vertices, edges, and triangles. Meanwhile, topology simplification deducts the number of holes, tunnels and cavities. Simplification that changes the geometry and topology of the original mesh is called aggressive simplification. Another idea from Erikson (1996) is that polygonal simplification can be separated into geometry removal (decimation), sampling and adaptive subdivision (refinement). Sampling is an algorithm that samples a model's geometry and then attempts to generate a simplified model that closely fits the sampled data.

2.4.1 Geometry Simplification

2.4.1.1 Vertex Clustering

The initial vertex clustering approach, proposed by Rossignac and Borrel (1993), is performed by building uniform grid of rectilinear cells, and then merging all the vertices within a cell, also can be call a cluster to a representative vertex for the cell. All the triangles and edges that stay completely in a cell are collapsed to a single point. Consequently, all these triangles and edges are discarded. Here by, the simplified mesh is generated.

The quality of vertex clustering could be improved by using some simple heuristics in finding the optimal vertex. Other than the work of Rossignac and Borrel (1993), Low and Tan (1997) proposed a slight variation on this heuristic motivated by a more thorough geometric reasoning. Their contribution is the making use of

“floating cell”. This floating cell algorithm dynamically picks the most important vertex as the center of a new cell, thus the quality is better.

Regularly, vertex clustering technique is fast and simple to implement. By recursively merging the clusters, the supercluster can be created. At the same time, it can be organized in a tree-like manner, allowing selective refinement of view-dependent simplification.

2.4.1.2 Face Clustering

Face clustering is similar to vertex clustering as both also group a number of vertices into a cluster. However, face clustering is less popular than vertex clustering. The algorithm starts by partitioning the original faces into superface patches (Kalvin and Taylor, 1996). Then, the interior vertices in each cluster are removed, and the cluster boundaries are simplified. In a final phase, the resulting non-planar superclusters are triangulated, thus creates a simplified model.

Garland (1999) creates multiple levels of detail for radiositized models by simplifying them in regions of near constant color. He uses the quadric error metric in simplifying the mesh’s dual graph.

Simplified mesh generated by face clustering has poorer quality compared to other operators. It is because the choice in choosing a right region to be a superface is already a tiresome and difficult work. Therefore, it is hard to create clusters that collectively provide an optimal partitioning to retain the important features. Some more, the geometry of the mesh is rarely optimized.

2.4.1.3 Vertex Removal

Vertex removal method iteratively keeps taking away a vertex in each time, and its incident triangles are removed. In doing it, holes may be created and thus triangulation is needed. Perhaps this is one of the most natural approaches. The first vertex removal method was foremost introduced by Schroeder *et al.* (1992). They remove the vertex based on the distance between the vertex and the plane by fitting a plane to the vertices surrounding the vertex being considered for removal. Vertices in high curvature regions have the higher priority to be retained compared to the vertices in flatter regions during simplification process. This is because eliminating the vertex in high curvature regions induces more error.

Same like Schroeder *et al.* do, other works also make use of the error metrics. Simplification envelops (Cohen *et al.*, 1996) algorithm removes the vertices randomly as long as the simplified surface lies within the envelopes. It is ensuring the simplified mesh stays within a specified deviation from the original mesh. Klein *et al.* (1996) also coarsen the model using vertex removal technique with maximum error bounds guaranty.

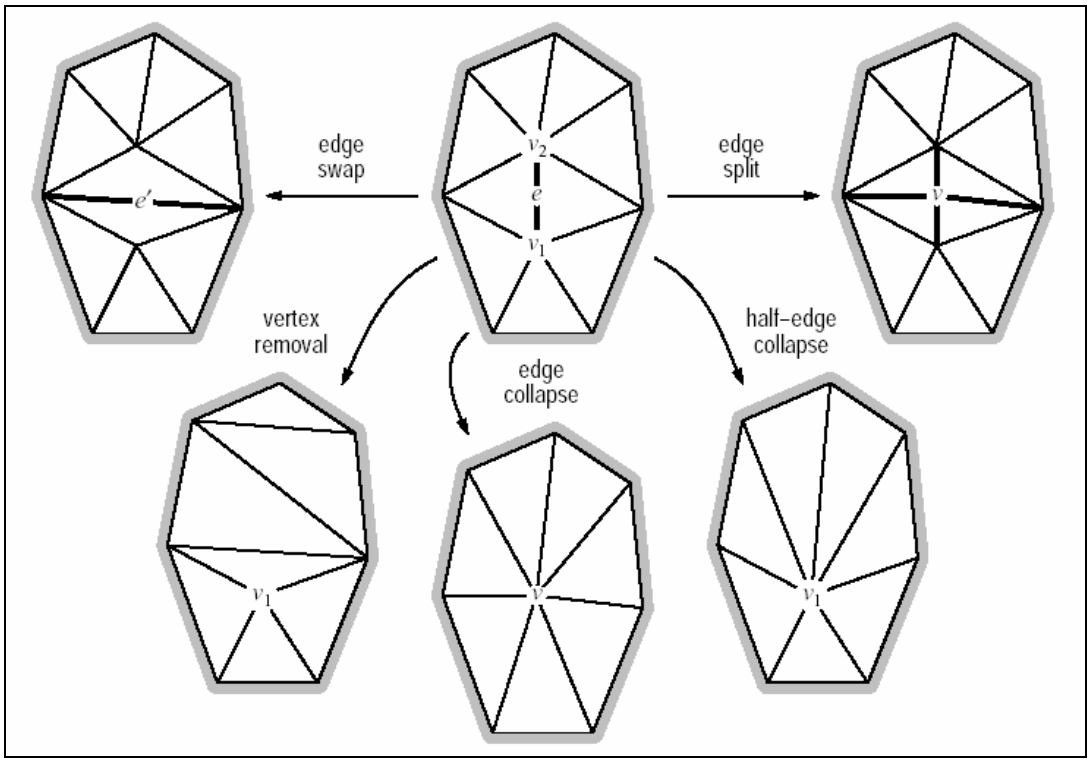


Figure 2.2 Local simplification operations (Lindstrom, 2003a)

2.4.1.4 Edge Collapse

Edge collapse is the most popular simplification operator, invented by Hoppe *et al.* (1993). This operator collapses an edge to a single vertex, continuously deleting the collapsed edge and its incident triangles. It is similar to vertex removal as it takes away a vertex at a time, yet, the choice of the vertex to be taken away is different. Also unlike vertex removal, no triangulation action is required because the resulting connectivity is uniquely defined

Progressive mesh (Hoppe, 1996) is the most famous work in existing edge collapse algorithms. A coarse mesh is keep adding details into it, explicitly, keep refining the mesh until a desired level of refined mesh is produced. It is done by performing the vertex split actions on the original mesh. This algorithm is wholly beneficial as the original coarser mesh can be obtained back by using the information used in vertex splitting process.

Edge collapse algorithm need to choose the order of edges to be collapse and also the optimal vertex to replace the discarded edge. Generally, these decisions are made by specifying an error metrics that depends on the positions of the substitute vertex. The sequence of the edges collapses usually is ordered from the cheapest to the most expensive action. In choosing the right replacement vertex, the lowest error metrics is used. Anyway, there are other factors may involve in these processes, including topological constraints, geometry constraints and handling of degenerate cases.

An identical edge collapse algorithm from Ronfard and Rossignac (1996) determine the edge collapsing sequence based on the maximum distance from the new optimal vertex to its supporting planes. A variation of this work, Garland and Heckbert (1997) perform the edge collapses by minimizing aggregate quadric error metrics, which is the sum of squared distances to the supporting planes. Whenever an edge is collapsed, the new vertex inherits the sum of quadric matrices of the edge’s vertices.

Haibin and Quiqi (2000) present a simple, fast and effective polygon reduction algorithm based on edge collapse by utilizing the “minimal cost” method to create multiresolution in real time 3D virtual environment development. Franc and Skala (2001) propose the parallel triangular mesh decimation using the edge contraction. The system is fast even sorting is not implemented. Its strength is proved according to the number of processors and the data size they used for testing.

Lindstrom and Turk (1998) create memoryless simplification using edge collapse, where geometric history in simplification is not retained. Then, the work was evaluated by Lindstrom and Turk (1999). Besides, memoryless polygonal simplification (Sourthen *et al*., 2001) applies vertex split operations in their level of detail generation.

Danovaro *et al.* (2002) compare two types of multiresolution representation: one is tetrahedron bisection (HT) and another one is based on vertex split (MT). Their work shows that HT can only deal with structured datasets whilst MT can work on unstructured and structured mesh. At the same time, based on their experiments, HT is more economic and the extracted mesh is lower in size.

An easier edge collapse method, commonly referred as half-edge collapse reduces an edge to one of its vertices. Hence, it generally produces in lower quality meshes than formal edge collapse since it allows no freedom in optimizing the mesh geometry. Anyway, as it allows the geometry to be fixed up-front, therefore it enables the polygon transferring and caching on the graphics card done efficiently. Besides, it is good in doing the view-dependent dynamic level of detail management. In addition, it is more concise and faster compared to edge collapse. This makes it suitable for progressive compression.

Another potential coarsening operation is called triangle collapse, which merges the three vertices of a triangle to an optimal vertex. It was used by Hamann (1994) and Gieng *et al.* (1997) for simplification. Since this operation is equivalent to perform two consecutive edge collapses, thus it also requires optimization of the substitute vertex. It has little bit faster computational time than the general edge collapse.

2.4.1.5 Vertex Pair Contraction

Vertex pair contraction is a variation of edge collapse that merges any pair of vertices from a virtual edge. There's possibility to merge disconnected components of a model by allowing topologically disjoint vertices to be collapsed. Not every pair of vertices can be collapsed, basically the subsets of pairs, which are spatially close to each other, are considered. Different strategies have been introduced and the selection of the virtual edge is usually orthogonal to the simplification method itself, including Delaunay edges (1997) and static thresholding (1997).

The work of Erikson and Manocha (1999) is the most notable for its dynamic selection of virtual edges, which allows increasingly larger gaps between pieces of a model to be merged. According to the work of Garland and Heckbert (1997), the vertex pair contraction can be generalized to a single atomic merge of any number of vertices. Thus, vertex pair contraction is considered the primitive generation of the edge collapse and vertex clustering simplification method.

2.4.2 Topology Simplification

Topology refers to the connected polygonal mesh's structure. Whilst, local topology of a primitive such as a vertex, edge or face is the connectivity of the primitive to their immediate neighborhood. If the local topology of a mesh is everywhere equivalent to a disc, then it is known as 2D manifold mesh.

Research on simplifying the topology of models with complex topological structure is gaining its attention. For large models with a large number of connected components and holes, such as mechanical part assemblies and large structures such as a building, it may need to merge the geometrically close pieces into larger individual pieces to allow further simplification (Erikson, 2000).

During topology simplification, it has to determine whether the manifold of mesh is required to be preserved or else. Topology preserving algorithm does not

close the holes in a mesh and hence the simplification is limited. Opposite to it, topology modifying algorithm aggregates separate components into assemblies, thus allows drastic simplification.

By default, the vertex pair contraction and vertex clustering are the simplification operators that modify the topology of models. These operators are not purposely designed to do so, but it is a byproduct of the geometry coarsening process. Anyway, these operators may introduce non-manifold mesh after simplification takes place.

Schroeder (1997) keeps on coarsening the mesh using vertex splits when the half edge collapse is limited during the manifold preserving coarsening process. However, only limited topological simplification is allowed, for example, disconnected parts cannot be merged. The method proposed by El-Sana and Varshney (1997) is able to detect and remove small holes or bumps.

Nooruddin and Turk (2003) implement a new topology-altering simplification, which able to handle holes, double walls and intersecting parts. Meanwhile, their work preserves the surface attributes and manifold of mesh at the same time. Liu *et al.* (2003) present a manifold-guaranteed out-of-core simplification of large meshes with controlled topological type by utilizes a set of Hermite data as an intermediate model representation. The topological controls include manifoldness of the simplified meshes, toleration of non-manifold mesh data input, topological noise removal, topological type control and sharp features and boundary preservation.

In many real-time applications, surface's manifoldness is less important. Hence, the vertex pair contraction and its derivatives are sufficient for topology simplification and it is significantly simpler to implement. Anyway, topology should be preserved well if the visual fidelity is crucial.

2.5 Metrics for Simplification and Quality Evaluation

Geometric error metrics is a measurement of geometric deviation between two surfaces during simplification. Because of the simplified mesh is rarely identical to the original, therefore metrics is used to check how similar the two models are. For graphics applications that produce raster image or the visual quality of the model is highly important, thus the image metric is more suitable at this moment.

2.5.1 Geometry-Based Metrics

Besides evaluating the quality of the simplified mesh, metrics is determining the way of simplification works. This mathematical definition of metrics is responsible in calculating the representative vertex and also determining the order of the coarsening operations. Anyway, each metrics has different ways in choosing its best manner for object simplification. On the other hand, the quality of the metrics is hardly to be evaluated in a precise way.

Typically simplification algorithms are using different kinds of metrics. Though, many of them are inspired by the well-known symmetric Hausdorff distance. This metric is defined using the Euclidean distance, which uses the shortest distance between a point and a set of points. In next sections, the well known metrics will be given away.

2.5.1.1 Quadric Error Metrics

The mathematical computation in metrics generation is usually reduced its complexity in order to make the simplification faster. There are many ways in calculating error metrics. For metrics based on maximum error, they are more conservative and fast. Meanwhile, the mean error metric is done locally on a small portion of the surface (Hoppe *et al.*, 1993).

Quadric error metrics (Garland and Heckbert, 1997) is based on weighted sums of squared distances. The distances are measured with respect to a collection of triangle planes associated with each vertex. This algorithm proceeds by iteratively merging pairs of vertices, which need not to be connected edge. Its major contribution is a new way to represent error using a sequence of vertex merge operations.

Quadric error metrics efficiently represents the metrics by using matrix. Anyhow, it only supports wholly geometry simplification. Garland and Heckbert (1998) extends the metrics to more than four dimensions to support surface attributes preservation other than geometry information. The matrix's dimension is based on how many attributes does a vertex own. It is particularly robust and fast. Besides, it produces good fidelity mesh even for drastic polygon reduction.

Quadric error metrics is fast, simple and guide simplification with minor storage costs. The visual fidelity is relatively high at the same time. In addition, it does not require manifold topology. That is, it allows drastic simplification as it lets holes to be closed and components to be merged.

2.5.1.2 Vertex-Vertex vs Vertex-Plane vs Vertex-Surface vs Surface-Surface Distance

Vertex-vertex distance measures the maximum distance traveled by merging vertices. While vertex-plane distance stores set of planes with each vertex, then errors are calculated based on distance from vertex to plane. Similarly, vertex-surface distance is distance between vertex and surface. It maps point set to closest points to simplified surface. Maximum distance between input and simplified surfaces is used to measure surface-surface distance.

2.5.2 Attribute Error Metrics

Quality evaluation can be done on image instead of model's geometry. Image metrics have been adopted in a number of different graphics applications. Therefore, the quality of the simplified mesh can be measured by evaluating the difference before and after the simplification happens. Some image metrics are quite simple. Probably the traditional metrics for comparing images is the *Lp* pixel-wise norm. Nonetheless, recently there are quite a number of researches focus on humans' psychology and vision to develop the computational models. In doing it, image processing and human visual perception is exploited.

Image processing techniques such as Fourier transform (Rushmeier *et al.*, 1995) or wavelet transforms (Jacobs *et al.*, 1995) can be used for this purpose. Besides, contrast sensitivity function also can be employed to guide the simplification process. It measures contrast and spatial frequency of changes induces by operation.

Human visual perception is utilized by Watson *et al.* (2000) by conducting a survey on the human's ability in identifying simplified models using different metrics. The durations of time spent to distinguish the different between the images for different metrics are analyzed. The results show that image metrics generally performed somewhat better than the geometry-based metrics used by Metro. Nevertheless, its robustness is uncertain.

2.6 External Memory Algorithms

The external memory algorithms are required in handling the data, which larger than the main memory. Because of the main memory cannot fit all the data, thus there is an external memory dilemma. As the speed of the data set is growing much faster than the RAM size. Therefore, these algorithms are essential to make the massive data sets loadable and run able in graphics applications. The initial work of external memory is proposed by Aggarwal and Vitter (1988). Later on, some

other fundamental paradigms for external memory algorithms are introduced. Until now, researches on external memory are continuous and never end.

There are two fundamental external memory concepts used in visualization and graphics applications, including batch computation and on-line computation. Batch computation has no preprocessing process and the whole set of data is processed. The way to make the data loadable is stream in the data in a few passes. Thus, only the portion of the data, which is smaller than the workstation's memory, is filled at one time and processed. Whilst on-line computation conducts preprocess to organize the data into a more manageable data structure in advance. This preprocess actually is a batch computation. Therefore, during runtime, only the needed portion of data is read into main memory by performing query on the well built data structure.

To accelerate the graphics rendering, geometry caching or prefetching techniques can be combined with the explained paradigms. It avoids the last minute data retrieval when the part of the data required to be displayed on screen. Else, it may slow down the rendering process as it needs to find the right portion of data from the data structure and then throw the required data to graphics card. Hence, if the part of the data, which is possible visible in the next frame is predicted, and put into cache first, consequently rendering will be speeded up.

In following section, discussion on computational model (Aggarwal and Vitter, 1988) is carried out. Then, batched computations, including external merge sort (Aggarwal and Vitter, 1988), out-of-core pointer de-referencing (Chiang and Silva, 1997), and the meta-cell technique (Chiang *et al*., 1998) are discussed. Next, on-line computation (Bayer and McCeight, 1972; Comer, 1979) is investigated too.

2.6.1 Computational Model

Disk access is two times longer than main memory access (Aggarwal and Vitter, 1988). In order to optimize the disk accessing time, a large block of contiguous data is loaded in one time. In handling large data sets, the size of input data (*N*) and the available main memory size (*M*) have to be found out. Continuously, the size of the data item (*B*) has to be determined. It is the size of memory used for every pass of data reading or data processing.

The performance of external memory algorithms is based on the total of the I/O operations (Aggarwal and Vitter, 1988). This I/O complexity is calculated by dividing the size of input data by size of the data item (*N/B*). The data size of scanned data may be reaching a few hundreds million of triangles. For instance, LLNL isosurface datasets used in work of Correa (2003) is 473 million triangles.

2.6.2 Batched Computations

2.6.2.1 External Merge Sort

Sorting is the primary practice in large data management. This is because sorting eliminates the need of randomly searching on a wanted value lies in the large dataset. External merge sort is a *k*-way merge sort, that is, *k* is *M/B*. *k* is the maximum number of disk block that can fit in main memory. The data is required to be loaded into main memory portion by portion in its contiguous place.

K-way merge sort has to load the whole data set with size *N*. If the current list *L* to be read is small enough to fit into main memory, then the data can be read into system in one time then sort it and put it back into its contiguous place. Else, *L* list is required to be spilt into *k* sub-lists, where each of them is equal in size. Then for each sub-list, the sorting is performed. There are lots of sorting algorithms nowadays, including bubble sort, quick sort, selection sort, tag sort and etc. After all the sub-lists are sorted, these sub-lists are merged.

Basically, merging is made by comparing the values from different lists. For example, like in two-way merge sort, two lists of data will be merged into a single data list. These two lists are read from beginning, and then compare the first elements from both lists. Whichever smaller element is put into output list and the array pointer is incremented. Continue checking on the following elements in both lists until all data elements are completely sorted.

A memory insensitive technique (Lindstrom, 2000a; Lindstrom and Silva, 2001) practically use the external merge *rsort* written by Linderman (2000) It is a combination of radix and merge sort technique, which the keys are compare lexicographically.

The way of the sorted *k* sub-lists of the entire data (*N*) to be merged in good I/O complexity is important. These *k* sorted-lists are merged and output these sorted items to disk in units of blocks. When the previous buffer finished its process, then the next block of the corresponding sub-list is read into main memory to fill up the allocated buffer. This process is repeated until all *k* sub-lists are merged successfully.

2.6.2.2 Out-of-Core Pointer Dereferencing

Usually data used in visualization or graphics applications is in indexed format. The triangular indexed mesh has a list of vertex coordinates and a list of triangles indices pointing to its relevant vertex coordinates. This data format is compact and save memory space as every vertex value is only stored once.

Using indexed mesh needs full searching on the vertex list to find its belonged vertices. If the data is small, then it is not noticeably memory inefficient. However, probably the vertex list or the triangles' indices or both of them are not fit able in main memory. Hence, pointer dereferencing is essential to generate a triangle soup instead of using the indexed mesh. Subsequently, it avoids the random accesses on disk. Random access is a must avoided task because single vertex retrieval may

need several block by block data readings (*B*) from the entire input data (*N*). It would require (*N*) I/O's in the worst case, which is extremely ineffective.

In order to make the massive data reading I/O efficient, thus the pointer dereferencing is used to replace the triangle indices by its corresponding vertices. Because of each triangle contains three vertices, so the pointer dereferencing also has three passes. In first pass, sort the first vertex using external merge sort technique. After all of the first vertices from triangle list are sorted, now the vertex list can be read in sequence. Keep replacing the vertex 1 with first vertex from vertex list, vertex 2 with second vertex from vertex list and so on. At that moment, all of the first triangle indices are filled with its equivalent vertices. In the second pass, sort the second vertices in the triangle list, and then dereference their equivalent vertices. Same works are acted upon the third vertices. Finally, triangle soup mesh is generated with every triangle indices are filled with its corresponding vertices.

This technique is applied in Lindstrom's (2000b) first out-of-core data simplification. Same with others' opinion, his work also avoids random access by using triangle soup mesh instead of indexed mesh. This data representation is two to three times more space consuming, but typically increase simplification speed by a factor of 15-20 (Lindstrom, 2000b). This process has also been used in (Chiang and Silva, 1997; Chiang *et al.*, 1998; El-Sana and Chiang, 2000; Lindstrom and Silva, 2001). These direct vertex information make the I/O complexity better.

2.6.2.3 The Meta-Cell Technique

The out-of-core pointer dereferencing technique is I/O efficient, but it is not suitable for final data representation in real time applications. Additionally, the vertices are duplicated quite many times. It causes the disk space overhead is bulky. To optimize both disk access and disk-space requirement, Chiang *et al.* (1998) proposed a technique called meta-cell technique. It is an I/O efficient partition scheme for irregular mesh. This technique has been adopted in out-of-core

isosurface extraction (Chiang *et al*., 1998; Chiang *et al*., 2001) and out-of-core volume rendering (Farias and Silva, 2001).

Basically the meta-cell technique divides the data into cells, which are equal in volume. Each meta-cell has own information and is normally loaded the whole from disk to main memory. The cell data is in indexed representation, called index cell set (ICS) by Chiang *et al.* (1998). This data representation contains a local vertex list and a local cell list, which point to the local vertex list. Hence, the vertex duplications are reduced compared to out-of-core pointer de-referencing technique. Only the vertices that fall into two different meta-cells are kept twice. Anyway, the more the meta-cells, the more the duplicated vertices it creates. However, it means each meta-cell is more refined and contains less information. Subsequently, the disk reading is faster. Therefore, there is always trade-off between query time and disk space.

The meta-cell technique has been extended for view-dependent simplification (El-Sana and Chiang, 2000). The meta-node tree is not only used in simplification but also accelerate the run time data query. At the same time, they also employ some additional features, such as prefetching, buffer management and also parallel processing.

2.6.3 On-Line Computations

A more efficient data searching probably is the tree based data structures for real time applications. The data in tree based data structures are well sorted and queries can be done faster. For external memory usage, the most famous tree based structure is the multiway B-tree by Bayer and McCreight (1972). Each end node holds *B* items. The branching factor is defined as the number of children of each internal node, except root node. This framework has been adopted in the works of Edelsbrunner (1983), El-Sana and Chiang (2000) and El-Sana and Varshney (1999). This algorithm is robust and capable to facilitate in many out-of-core visualization and graphic domains.

Tree based data structure significantly reduce the I/O complexity compared to direct data searching on the external memory mesh. Usually binary tree or even octree with branching factor two or eight can be used. Anyway, it still requires accessing a certain number of items in order to get the demanded item. Therefore, it is better to externalize the data structure to *B*-tree-like data structure. It can be done by increasing the branching factor for the internal node. Automatically, the tree's height is decreased while the number of items in each node is increased. As a result, it can trim down the data searching time.

2.7 Out-of-Core Approaches

One of the reason why out-of-core simplification approaches exist is the majority of the previous methods for in-core simplification are ill-suited in out-of-core setting. The prevailing approach to in-core simplification is to iteratively perform a sequence of local mesh coarsening operations (Section 2.4.1) that locally simplify the mesh by removing a primitive geometry at one time. The order of operations performed relies on the error metrics they use, which discard a simplex according to their visual importance. In any case, manipulating the order of coarsening operations from lowest error to highest error impose a certain number of memory and computational time.

In order to make the massive mesh able to be simplified, usually the mesh need to be partitioned until it is suitable to be simplified in available main memory. Therefore, it is common to group the mesh into clusters. Basically those triangles, whose vertices belong to three different clusters, are remained during the simplification process. Ideally the partitioning is done to minimize the given error measurement and the representative vertex is chosen based on certain error metrics.

Most of the in-core methods use indexed mesh representation, where the triangles are specified as indices and their corresponding vertices are referred. For out-of-core simplification to be viable, random accesses must be avoided at all costs. As a result, many out-of-core methods make use of a triangle soup mesh

representation, where each triangle is represented independently as a triplet of vertex coordinated. The triangle soup can be generated by using the previously discussed external memory algorithms.

Varadhan and Manocha (2002) proposed an external memory algorithm for fast display of large and complex geometric environment. This algorithm uses a parallel approach to render the scene as well as fetch objects from the disk in a synchronous manner. Besides, novel prioritized prefetching technique that takes into account LOD switching and visibility-based events. Correa *et al.* (2002) also present an out-of-core preprocessing algorithm, which uses multiple threads to overlap rendering, visibility computation and disk operation. Besides, from-point prefetching method is implemented. Crack prevention is introduced by Guthe *et al.* (2003) by appropriately shades the cut using fat borders in their hierarchical levels of details algorithm.

Borodin *et al.* (2003) also propose an out-of-core simplification with guaranteed error tolerance. The algorithm consisted three processes, includes memory insentive cutting, hierarchical simplification and memory insensitive stitching. Vertex contraction is their simplification operator as they claimed it produces better quality but slower computation time. Shaffer and Garland (2001) also propose an adaptive simplification of massive meshes, which can generate progressive transmission. It uses edge contraction in simplification process.

There are three distinct approaches to out-of-core simplification techniques: spatial clustering, surface segmentation and streaming (Lindstrom, 2003b). For each approach, uniform and adaptive partitioning will be distinguished.

2.7.1 Spatial Clustering

Clustering decisions is based on either connectivity or geometry of the mesh, or both. Because of computing and maintaining the connectivity of a large mesh out-of-core is difficult, perhaps the simplest approach is partitioning the vertices spatially.

Determining cell containment performs vertex clustering. No topological constraints are considered.

Spatial clustering's main idea is to partition the space that the surface is embedded into simple convex 3D regions. Next, merge the vertices in the same cell. Because the mesh geometry is often specified in a Cartesian coordinate system, a rectilinear grid gives the most straightforward space partitioning. It is similar to vertex clustering algorithms (Section 2.4.1.1). Figure 2.3 illustrates the how the spatial clustering works.

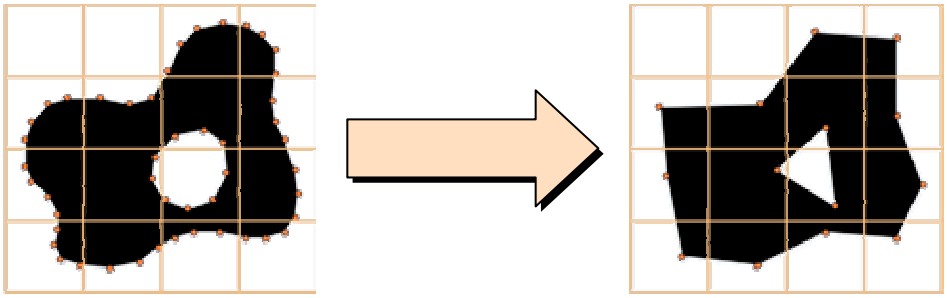


Figure 2.3 Spatial Clustering process (Lindstrom, 2003a)

Uniform spatial clustering is simplest partitioning, which partitions the space into grid equally. It sparse the data structure represents occupied cells. By minimizing the quadric error, the representative vertex can be calculated. The triangles whose vertices fall in three different cells are kept at last. These processes are practically done by Lindstrom (2000) in his out-of-core simplification (OOCS). Later on, memory insensitive clustering (OOCSx) approach, which is independent on simplified mesh's size, is introduced (Lindstrom and Silva, 2001). It first scans the triangles, and then computes the plane equation, saves the cluster ID and plane equation for each vertex and saves the non-degenerated triangles to triangle file. Sort plane equation file on cluster ID then compute cluster quadrics and output optimal vertices. Then, re-indexing process take place to sort the triangle file, scan and replace the cluster ID with vertex ID, repeat to every vertex field. This work is extended to run-time view-dependent rendering by preserving some surface attributes (Lindstrom, 2003c).

For uneven triangles distributed mesh, where many triangles may fall in a region whilst the other part may have very little number of triangles, it is impractical to use the uniform clustering. It is because the uniform spatial clustering technique doesn't adapt to surface features nicely. It does not imply well-shaped clusters. Besides, it may create many uneven or disconnected surface patches. On the other hand, the fixed-resolution limits the maximum simplification. To overcome these weaknesses, adaptive spatial clustering technique is proposed.

In adaptive clustering, the cell geometry is adapted to surface condition. For example, uses smaller cells in detailed regions. Garland and Shaffer (2002) present a BSP tree technique in space partitioning. Firstly, the quadrics on uniform grid are accumulated. Secondly, the PCA of primal/dual quadrics is used to a suitable space partitioning condition. In second pass, the mesh is reclustered. Fei *et al.* (2002) propose an adaptive sampling scheme, called the balanced retriangulation (BT). They use Garland's quadric error matrix to analyze the global distribution of surface details. Based on this analysis, a local retriangulation achieves adaptive sampling by restoring detailed areas with cell split operation while further simplifying smooth areas with edge collapse operations.

2.7.2 Surface Segmentation

Fundamentally, spatial clustering partitions the space that the surface lies in. This method partitions the surface into patches so that they can be further processed independent in-core. Then, every patch is simplified to a desired level of detail using in-core simplification operator. For instance, one can simplify the triangles in the patch using the edge collapse. After simplification, the patches are stitched back.

As in spatial clustering, surface segmentation could be uniform by partitioning the surface over uniform grid, or adaptive by cutting the surface along feature line. Figure 2.4 shows the diagram of process flow in surface segmentation method.

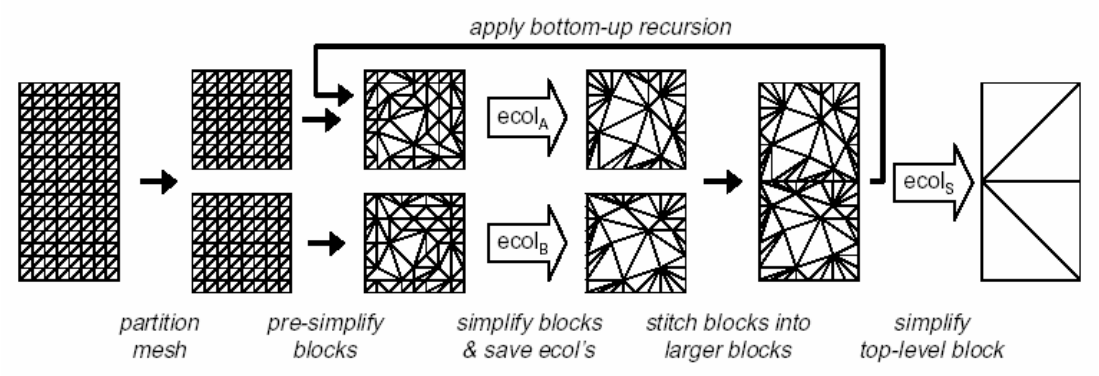


Figure 2.4 Block-based simplification using uniform surface segmentation and edge collapse (Hoppe, 1998b)

Bernardini *et al.* (2002) propose a uniform surface segmentation algorithm with constraints that the boundary intact to allow future merging. It is quite easy to implement and have higher quality than spatial clustering simplification method. But, it is two times slower than spatial clustering method. Additionally, the output of the simplified mesh can't span a few level of detail.

An adaptive surface segmentation algorithm is proposed, named OEMM (Cignoni *et al*., 2003c). It uses octree-based external memory mesh data structure. The grid is rectilinear and the data structure is unspecific that not only created for simplification purpose. It is similar to Bernardini *et al.* (2002), but the octree adapts in suitable resolution to match better surface detail, the edges can be collapsed across patch boundaries and the output is a progressive mesh.

Another adaptive approach, which is fully depends on error-driven surface segmentation is introduced by El-Sana and Chiang (2000). This technique can preserve the correct collapsing order and thus ensure the run-time image quality. Besides, features like prefetching, implicit dependencies and parallel processes are implemented. It computes mesh connectivity, initialize priority queue on disk. Then, for each bath of lower-error edges, dequeue the edge and load incident faces into RAM, collapse edges whenever possible, recomputed error then write back to disk. It repeats until desired accuracy is achieved.

Prince (2000) uses octree partitioning and edge collapse like OEMM do. He is able to create and view progressive mesh representation of large models. He uses octree partition, edge collapse simplification operator but need to frozen the path's boundary. There is another adaptive surface segmentation method is by Choudhury and Watson (2002) whose propose a simplification in reserve. It is an enhancement of *RSimp* (Brodsky and Watson, 2000) to become *VMRSimp*. Brodsky and Watson use refinement based on vector quantization. Their work is generally believed faster as the refinement is take shorter time than simplification does. Anyway, it has poorer quality as refinement leads to lower quality result.

2.7.3 Streaming

Streaming treats a mesh as a sequenced stream of triangles. For each time, read a triangle, process it then write it in a single pass. Later on, in finite in-core stream buffer, indexed submesh is built up. For the triangles that loaded into buffer, in-core simplification is performed. In order to make sure buffer contains sufficiently large and connected mesh patches, it requires coherent linear layout of mesh triangles.

In stream buffer properties, there are processed region, buffered region and unprocessed region. One or more loops of edges that divide mesh into processed and unprocessed regions. Indexed triangles read from input boundary and write to output boundary. The stream boundary sweeps continuously over mesh. Therefore, no stitching is needed unlike conventional surface segmentation method. Figure 2.5 shows the stream boundaries.

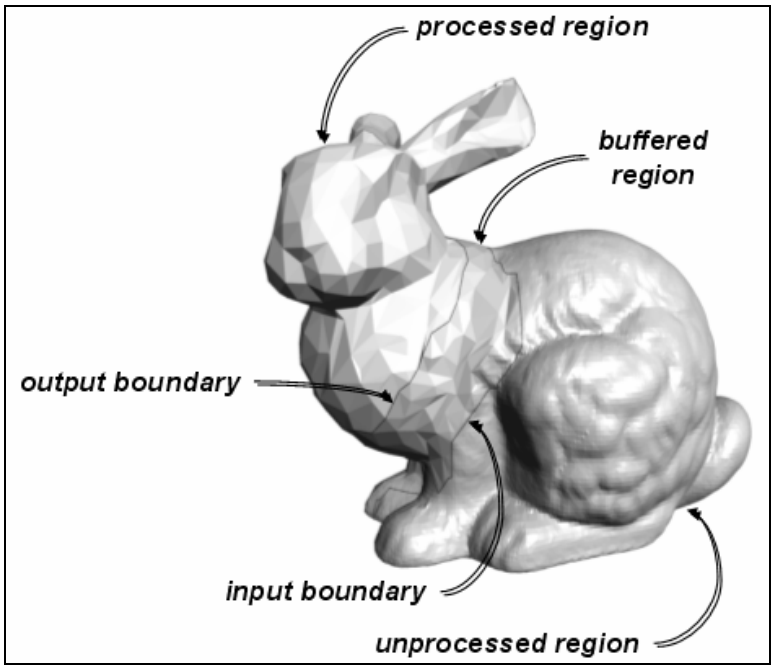


Figure 2.5 Streaming properties (Lindstrom, 2003a)

A new approach in out-of-core mesh processing technique can be adapted to perform computation based on new processing sequence (Isenburg and Gumhold, 2003; Isenburg *et al*., 2003a) paradigm. Processing sequence for large mesh simplification (Isenburg *et al.*, 2003b) represents a mesh as a particular interleaved ordering of indexed triangles and vertices. This representation allows streaming very large meshes through main memory while maintaining information about the visitation status of edges and vertices. Stream-based edge collapse (Wu and Kobbelt, 2003) reads the input from a data stream and writes the output to another stream. It is good because it doesn't have stitching artifacts, but its geometry hashing overhead and cannot differentiate stream boundary from surface boundary.

2.7.4 Comparison

The Table 2.1 shows the comparison between these out-of-core simplifications based on different attributes.

Table 2.1 Comparison between 3 types of out-of-core simplification

Characteristics	Spatial Clustering	Surface Segmentation	Streaming
Concept	Cluster vertices based on spatial proximity	Cluster vertices primary based on error	Cluster vertices based on spatial or error-based criteria
Speed	Fast (50-400K tps)	Slow (1-10K tps)	Fast and highly parallelizable via pipelining
Quality	Low	High	Governed by user specific stream buffer
Suitable situation	Time or space is at premium.	Quality more important than speed, need progressive streaming, view-dependent rendering and preserve topology	Need to preserve connectivity, need high quality
Main drawback	Low quality, topology not preserved	Slow	Not clear how to create multiresolution meshes

Each out-of-core simplification technique has its cons and pros. So, in order to choose a better one, select one which most suites the type of application it's applied on. In this way, the optimum output mesh can be produced.

2.8 Analysis on Out-of-Core Approach

2.8.1 Advantages and Disadvantages

Nowadays, models are well beyond most core memories can be handled. The sizes of these datasets rise drastically from range 10^7 to 10^9 faces. The out-of-core approaches apparently solved simplification problems on datasets, which are larger than main memory. These out-of-core techniques use virtual memory to put the data that are not used into hard disk and then put in the portion of data needed for rendering into main memory. Therefore, it makes the display of extremely large datasets possible.

Besides, out-of-core approaches could speed up development. For example, Lindstrom (2000) presents an extremely fast simplification model that can process 400K triangles per second on desktop PC. It is the nearly impossible achieved by other in-core simplification methods. On the other hand, it could handle highly variable level of detail, even extreme close-ups revealing new detail.

Even though out-of-core approaches contributed a lot in making the rendering of massive datasets possible, it has its weakness. That's it; random access on must be avoided. This is because the disk access is slow and hence need to minimize this process. It is unlike main memory access, which is fast and convenient.

2.8.2 Comparison: In-Core and Out-of-Core Approach

In-core simplification and out-of-core simplification have their similarities and differences. When looking into the purpose of simplification, they have a same ambition, that's to simplify the input mesh to a certain level of detail. They both discard degenerated triangles. Their quality determined by the degree of similarity between simplified mesh and original mesh. However, they have few differences as well (refer Table 2.2).

Table 2.2 Comparison between in-core approach and out-of-core approach

Characteristics	In-core	Out-of-core
Type of Memory	Main memory.	Use secondary memory for unused data, main memory for data, which will be displayed.
Size of datasets	Must smaller than main memory.	Can be larger than main memory, maximum data size depends on algorithm's strategy. For example, Lindstrom (2000) depends on output mesh size whilst Lindstrom and Silva (2001) is independent of the available memory on computer.
Simplification operators	Local simplification, such as vertex removal, edge collapse, triangle collapse, vertex clustering, vertex pair contraction, etc.	Can be categorized in three groups, which are spatial clustering, surface segmentation and streaming. Internal operation can be done by in-core simplification operator, for example: edge collapse in OEMM (Cignoni *et al*., 2002) and vertex clustering (Lindstrom, 2000).
How it works?	Directly place the mesh into main memory and simplify it. For example, edge collapse and vertex clustering.	Convert mesh into a data structure in preprocess and store it on disk, then extract the portion of data that is being used to main memory during run-time.
Speed	Depends on size of input mesh.	Depends on algorithm. But eventually faster than in-core method.
Quality	Depends on simplification operator.	Depends on simplification method.

2.8.3 Performance Comparison: Existing Simplification Techniques

For comparison between a few implemented simplification techniques, a comparison can be made between in-core and out-of-core simplification. The basis for many out-of-core simplifications, Out-of-Core Simplification (OOCS) by (Lindstrom, 2000) is the initial work in out-of-core simplification. It can simplify 400K triangles per second and require 63-72 bytes to represent a triangle. Nevertheless, its quality is quite low as no connectivity is remained. Table 2.3 compare the OOCS (Lindstrom, 2000) to two in-core simplification techniques, QSlim (Garland and Heckbert, 1997) and memoryless simplification (Lindstrom and Turk, 1998). QSlim is one of the fastest vertex merge algorithm (Brodsky and Watson, 2000). While memoryless simplification is an efficient simplification that no needs to retain history of simplified mesh in memory.

Table 2.3 Simplification results of running QSlim, memoryless simplification (Mless) and OOCS. All results were gathered on a 195 MHz R 10000 SGI Origin with 4GB of RAM and a standard SCSI disk drive (Lindstrom, 2000)

Model	T_{out}	RAM (MB)			Time (h:m:s)		
		QSlim	Mless	OOCS	QSlim	Mless	OOCS
Dragon T=871,306	244,562	213	134	28	5:31	11:59	0:16
	113,090	214	134	11	5:55	14:12	0:12
	47,228	214	134	7	6:06	15:21	0:10
Buddha T=1,087,716	204,750	250	166	26	7:13	16:58	0:17
	62,354	251	166	8	7:35	19:19	0:12
Blade T=28,246,208	507,104	-	3,185	63	-	12:37:25	5:02
Statue T=386,488,573	3,122,226	-	-	366	-	-	1:59:20

From Table 2.3, we can see that RAM usages in-core approaches (QSlim and Memoryless Simplification) are depends on the size of the input mesh. When the RAM usage is bigger than 4GB, blade cannot be process by QSlim method. However, it still can be process by memoryless simplification because memoryless

simplification doesn't retain the history of simplified mesh free up some space for this process. Nevertheless, statue with input size 400 millions of triangles cannot be processed by memoryless simplification anymore as it cannot be fit into limited RAM memory. It is not a problem for OOCS as it doesn't depend on input mesh's size. OOCS can process any mesh with constraint that the size of the output mesh mustn't larger than RAM size. While being much more memory efficient, this out-of-core simplification technique also orders of magnitude faster.

OOCS is fast, but the quality is looser because it doesn't perform adaptive sampling. Further, since OOCS does not reply on connectivity information, it has no way of detecting boundary edges (or non-manifold edge). To make the quality better, hybrid approach could be considered, that is, first, perform OOCS on a large model, then follow by slower but accurate in-core simplification (Lindstrom, 2000a).

Even though OOCS can display lots of massive data, however, it encounters problem when dealing with the output size, which is larger than available main memory. Referring Table 2.4, OOCS is faster than OOCSx (Lindstrom and Silva, 2001) between two to five times when output mesh remains smaller than RAM size. But, in one case, for simplification of blade, OOCSx is faster than OOCS. The reason is OOCS ran out of memory, and numerous page faults occurred. Another case is 15.5MB RAM even is not enough for OOCS to simplify the fluid. Memory usage of OOCSx depends on size of the input mesh, whereas memory usage for OOCS is proportional to size of output mesh. Additionally, OOCSx only use arbitrary little main memory (5MB or 8MB RAM in this simplification process). Contrary, OOCS use all available main memory for displaying the output mesh.

In (Lindstrom, 2003c), Lindstrom has improved insensitive algorithm (Lindstrom and Silva, 2001), which is remarkable fast and yields an effective triangle processing rate of roughly 20K to 60K triangles per second. The system is view-dependent. Other than that, he also pointed out that El-Sana and Chiang (2000) can simplify at 5,300 triangles per second with input mesh 1.2 million triangles. But, their method will steadily reject the input mesh when it grows larger. Prince (2000) can produce a 1000 triangles per second on 11.4 million triangles' mesh, however, it requires more than 512MB RAM to do it.

Table 2.4 Run-time performance of OOCS and OOCSx. Blade were computed on Linux PC with 512MB RAM and two 800 MHz Pentium III processor. Statue and fluid are simplified on SGI Onyx2 with forth-eight 250MHz R10000 processor and 15.5GB RAM. (Lindstrom and Silva, 2001)

Model	T_{in}	T_{out}	RAM:disk (MB)		Time (h:m:s)	
			OOCS	OOCSx	OOCS	OOCSx
Blade	28,246,208	507,104	49:0	5:4,850	2:46	13:14
		1, 968,172	160:0	5:4,899	3:11	14:30
		7,327,888	859:0	5:4,993	19:14	17:04
Statue	372,963,401	3,012,996	261:0	8:64,004	44:22	2:7:24
		21,506,180	3,407:0	8:64,256	51:23	2:49:30
Fluid	467,614,855	6,823,739	588:0	8:80,334	55:56	3:11:48
		26,086,125	3,427:0	8:80,510	1:08:48	3:23:42
		94,054,242	-	8:80,345	-	4:19:09

Simplification using Octree-based External Memory Mesh (OEMM) by (Cignoni *et al*., 2003c) eventually faster than in-core simplification method: QSlim and RAM-QEM (implementation of QEM in main memory) and their RMS errors are quite similar. However, it is much slower than OOCS even though the error metrics is much smaller (higher quality) than OOCS. Besides, Cignoni *et al.* (2003c) can produce up to 13K triangles per second, but the output is not directly usable in view-dependent refinement. Table 2.5 shows the simplification of a Happy Buddha (1,087, 716 faces) on PIII 800MHz PC with 128MB RAM.

Table 2.5 Simplification on Happy Buddha using four different codes (Cignoni *et al*., 2003c)

Code	Simpl. faces	RAM (MB)	Time (s)	Tps rate	RMS err
QSlim v2.0	18,338	195	60	17.4K	0.0131
RAM-QEM	18,338	160	58	18K	0.0125
OEMM-QEM (Preprocess)	-	4	58	-	-
OEMM-QEM (Simplify)	18,338	60	48	21.7K	0.0129
OOCS	19,071	36	15	69.5K	0.0245

An approach making the out-of-core simplification with a guaranteed error tolerance (Borodin *et al*., 2003) is implemented using vertex contraction technique instead of vertex clustering. Even the error is minimized until lower than QSlim (Garland and Heckbert, 1997) and output's quality is high, the simplification time is relatively slow. Plus, their work doesn't show the statistics of simplified mesh with size larger than 35K triangles (See Table 2.6).

Table 2.6 Reduction and performance rates for four standard models using a 1.8GHz Pentium IV PC with 512MB main memory (Borodin *et al*., 2001)

Model	T_{in}	T_{out}	Error	Simplifcation time (h:m:s)	Rate (tps)
Armadillo	345 944	33 780	0.129	0:05:06	826
Happy Buddha	1 087 716	32 377	0.170	0:19:28	728
David 2mm	8 254 150	25 888	0.178	2:22:02	762
Lucy	28 055 742	26 772	0.163	8:03:57	779

A multiphrase approach (Garland and Shaffer, 2002), which operates by combining an initial out-of-core uniform clustering phase with a subsequent in-core iterative edge contraction phase performs very well in simplification process. This technique produces higher quality, better distribution of triangles than uniform spatial clustering. But, higher grid resolution needed in the first pass causing the more memory is consumed. Besides, it is still output sensitive. They have compared their results with OOCS (Lindstrom, 2000), adaptive out-of-core clustering (Shaffer and Garland, 2001), and QSlim (Garland and Heckbert, 1997). Results show that it is able to simplify polygonal mesh of arbitrary size, like OOCS, but it is able to generate much higher quality approximations at moderate to small output sizes. Indeed, it consistently produces approximations of quality comparable to QSlim, but using considerably less running time and memory, both asymptotically and in practice.

Guthe *et al*. (2003) propose a very efficient hierarchical level of details on complex environment and filling cracks created during simplification process by using shaded fat borders. This algorithm is run on a 1.8GHz Pentium 4 PC with 512MB memory and ATI Radeon 9700Pro and the results are tremendously good.

Their work is compared with out-of-core algorithm without crack filling and in-core rendering. The frame rates that it produced are adequate to generate an excellent real-time application probably due to the good VGA card they used.

Correa (2003) proposes a new algorithm in out-of-core simplification, consisting two phrases of work as well, which is preprocessing and runtime. In building the octree, a finer tree creates a more precise view-frustum. Coarser granularity reduces traversal time, decreases vertex replication but increases possibility of fetching and rendering of invisible geometry. LoD generations are created by vertex clustering technique. Besides, occlusion culling and sort-first parallel rendering are also implemented.

For preprocessing step, 2.4 GHz Pentium IV computer with 512 MB of RAM, 250 GB IDE disk and a NVIDIA GeForce Quadro FX 5200 Graphics card is used. During octree generation, based on his thesis's figure, granularity of 15K vertices per leaf needs roughly six minutes to generate it. Whilst LOD generation for the original data and four simplified models needs approximately eight minutes of time with additional data size of 268MB. This algorithm is fairly good in its speed aspect. Nevertheless, due to his implementation constructs static LOD, while Lindstrom (2003c) generates view-dependent LOD, and hence comparison is hard to be made between these algorithms. Besides, no figures on simplification time are shown. Subsequently, it is difficult to compare its efficiency with other existing algorithms.

Comparison between performance of adaptive and uniform clustering methods have been carried out by Shaffer and Garland (2001). Tool Metro (Cignoni *et al*., 1998) is used to measure error metrics. The results show that error in coarse approximation is reduced about 20%. At the same time, finer resolution is dropped around 10% too. This shows that adaptive gives better quality approximation. However, the time consuming to simplify the mesh is varied from around 2.5 to 3 times as much as that required for uniform clustering. As a short conclusion, adaptive clustering induces better quality mesh but slower than uniform clustering do.

In streaming simplification approach, it generates higher quality than spatial clustering and surface segmentation simplification techniques with low memory

requirement. Most recent work by Isenburg *et al*. (2003b) enables full connectivity and geometry information is available for the active elements of the traversal even the mesh access is restricted to a fixed traversal order. This provides seemless and highly efficient out-of-core access to very large meshes for algorithms that can adapt their computations to this fixed ordering. Some models simplified using this algorithm by using 800MHz Linux PC. This is suitable to make a comparison to works of (Wu and Kobbelt, 2003; Lindstrom and Silva, 2001; Cignoni *et al*., 2003c) as their works are run on 800MHz Pentium 3 with 880MB RAM. The quality of this approach is apparently compatible with other out-of-core approaches. Anyway, the neighbour triangles have to be grouped together.

From all these recently published algorithms, the findings show that the multiphrase approach (Garland and Shaffer, 2002), Efficient View-Dependent Out-of-Core Visualization (Guthe *et al*., 2003), Out-of-Core Visualization of Large Datasets (Correa, 2003) and large mesh simplification using Sequence Processing (Isenburg et al, 2003b) give an appropriate good quality as the same time a pleasant processing time as well. OOCS (Lindstrom, 2000) would be the greatest if the simplification time is the most vital element instead of quality.

2.9 Appearance Attribute Preservation

Many simplification algorithms simplify geometry data but pay no attention to surface preservation. For sure, geometry simplification is vital in reducing the gigantic data size. However, appearance-preserving also important to retain the surface attributes after simplification process. Normally, the surfaces attributes need to be preserved during mesh simplification include surface position, normal, surface curvature, color attributes and texture attributes.

From beginning, surface preservation is often done separately with geometry simplification. In accomplishing this, decouples the sampling rates of the surface attributes by storing the object's color and normal vectors in texture and normal maps respectively. Then make sure the bounds on both the surface and texture

deviations by filtering the model's surface position. Meanwhile, the color and normal attributes are filtered during rendering time. Thus, it guarantees the surface attributes are sampled appropriately within certain error tolerance.

The mapping algorithm presented in (Bajaj and Schikore, 1996) allows the preservation of arbitrary scalar fields across a surface. The scalar fields are linearly interpolated across the mesh's triangles. They track geometric and attribute errors in mesh's faces to obtain error-bounded simplification of meshes with attributes.

Hughes *et al.* (1996) investigated the simplification on colored Gouraud-shaded meshes produced by global illumination algorithms. They transform the vertex colors into a more perceptually linear space before simplification takes place.

Certain *et al.* (1996) added surface color to a wavelet-based multiresolution framework for surface subdivision (DeRose *et al*., 1993). They generate two lists of wavelet coefficients for geometry and color data. Surface parameterization is also used to store colors in texture maps to render as textured triangles during rendering process.

Hoppe (1996) explicitly includes surface attributes in the error metric of Hoppe *et al.* (1993). The scalar deviation is measured as a sum of squared Euclidean distances in the attribute space. However, it doesn't show the impact after incorporating the attributes preservation in the final appearance of simplified object.

Erikson and Manocha (1998) present a point-wise quadric error method to measure the maximum attribute deviation in Euclidean attribute spaces. Associated with each vertex is an attribute volume for each measured attribute. Each attribute volume is initially a point in the attribute space. As vertex pairs are merged, the attribute volumes grow to contain the volumes of both vertices.

Cohen *et al.* (1998) develop an algorithm, which is capable to reparameterize texture maps as a surface is simplified. By tracking parametric instead of geometry correspondence, their method bounds the displacement of a vertex on the mesh with any given texture coordinate, which is the right metric for texture mapped surfaces.

Unlike the method mentioned previously, the surface attributes' simplification is possible to be completed successfully using a single metric. As discussed in the section of quadric error metric (Section 2.5.1.1), extended quadric error metric (Garland and Heckbert, 1998) is proficient in retaining surface attributes during simplification development. In conjunction, Hoppe (1999) continue enhancing this metric by using a wedge-based mesh data structure to capture the attribute discontinuities, such as surface creases and material boundaries. Besides, he permits simultaneous optimization of these multiple attributes vectors.

Similar to Garland and Heckbert (1998) and Hoppe (1999), Lindstrom (2000a) has extended the vertex representation from three dimensions to multiple dimensions. He is using the concept of utilizing single metric in geometry and attributes simplification. Anyhow, Lindstrom (2000a) creates the texture coordinates himself by choosing the most suitable texture coordinates based on the given vertex positions.

2.10 Summary

This chapter has covered mostly all the critical topics in level of detail field. Mostly all the main processes involved in developing a full simplification model have been discussed in depth, whether for in-core simplification or out-of-core simplification.

This literature review surveyed the main processes in developing an in-core simplification application, which are LOD framework, LOD management, LOD generation and error metrics. First, we need to determine which type of LOD framework that we are planning to use. Every LOD framework has its pros and cons. Suitable LOD has to be chosen based on the type of application it applies in. View-dependent offer higher fidelity as no extra polygons are rendered based on viewing perspective. However, it needs more calculation on the viewing perception. Contrary, discrete LOD may offer less accuracy, but its computation is less. Anyway, using any of these LOD frameworks brings cons and pros. Hence, good care is needed in handling its weakness.

Even though many ideas developed so far in LOD management, but, there are still no criterion can be said is the most optimum technique. Distance or screen space size is the traditional way in LOD management, whilst visual perception is the most up to date LOD management criterion. There's always trade in between precise level of detail selection with the high computation time and high cost in eye tracking device.

Geometry simplification reduces number of polygons. To eliminate the holes and cracks created, topology simplification must be applied. Many simplification operators invented and enhanced so far. Same concept goes to this area, higher quality mesh always need more computation time than others do. Edge collapse creates nice output mesh, whereas the vertex clustering is fairly fast.

To measure the error metrics, there are a few methods in doing it. This is to compare how accurate the simplified object with the original object. Either it is geometry-based metrics or attributes error metrics. Among these metrics, quadric error metrics is the robust and well-known error metrics.

Out-of-core approach needs more works than in-core do. That is, here, external memory management and out-of-core simplification methods are considered necessary. Before the data going through the simplification, external memory management is making sure that it is loadable into main memory first. Later on, out-of-core simplification is carried out. It partitions the space using spatial data structure or subdivides the space uniformly first. Then, it uses the existing simplification operator to simplify the mesh in every partitioned space. The process is pretty tricky and need extra care to make sure it runs without causing any memory leaking problem.

In addition, a full analysis has been carried out to investigate its cons and pros, to compare between in-core and out-of-core methods and to study the performance distinctions between existing out-of-core algorithms.

Last but not least, the well-known surface preservation techniques have been revealed. At starting, simplification on geometry and attributes are made separately.

Later on, simplification on geometry and surface attributes is performed on each vertex by using single metrics. These recent methods are simple and straightforward to be implemented.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Rapid technology growth in modern 3D scanning technology and the high complexity of computer simulations has led to a boost in the size of geometry datasets. Even the most powerful graphics hardware also cannot handle the rendering of the extremely massive data, especially in real-time application. Besides, in many applications, surface attributes are important to show the details of the mesh. Therefore, automatic simplification on massive datasets while preserving its surface attributes is proposed.

This out-of-core simplification starts with data processing. Continuously, data is represented in an octree structure and then the model is simplified using a new variation of vertex clustering technique. During run-time, the portion of the visible mesh is rendered based on distance aspect. This approach is fairly simple and efficient.

The methodology is organized in a few sections. First, the algorithm framework is employed. Next, the preprocess performing the data processing, octree construction and simplification is given. Lastly, the run-time rendering is discussed and finally a short conclusion is brought.

3.2 Algorithm Overview

This paper introduces an approach for end-to-end and out-of-core simplification and discrete visualization of large surfaces. Besides, appearance preservation is proposed as well. Here, the arbitrarily large datasets, which are larger than memory size, now can be visualized by using a sufficient amount of disk space (a constant multiple size of the input mesh). The preprocess work starts with data preprocessing and then an octree is constructed to partition the space efficiently. Consequently, a modified vertex clustering simplification is preceded. Finally, the multiresolution output mesh is displayed during run-time. The off-line phrases are performed on secondary memory whilst the run-time system only pages in the needed parts from the octree for rendering purpose. The framework overview is shown in Figure 3.1.

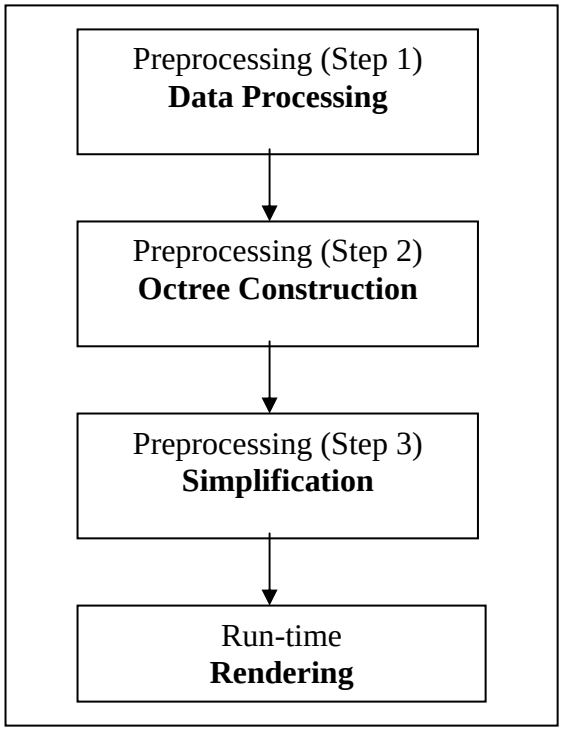


Figure 3.1 Framework overview

Algorithm starts with data processing process. It involves data loading into our system and dereferencing of triangle indices to their corresponding vertices. The experimental data is in PLY data format. It is one of the common file formats in storing the large datasets. However, these raw data are an indexed mesh. Even though the format is compact, the processing time is slow. Thus, it needs to be

further processed before proceeding to simplification process. Hence, by using data dereferencing, a list of triangle is pointed to its vertices so that a triangle soup mesh is generated.

Secondly, an octree is constructed to divide the loaded data into spatial space. The purpose is to make sure the data become easier and neater. By using it, the simplification and data extraction processes become simpler. Most important is it can accelerate the data query during rendering process later on. The triangular mesh is subdivided into its appropriate location. Because of the datasets size is too large to the available main memory size on commodity computer; hence the data in each octree node is kept in its end node file. The end node files size is small enough to fit in main memory and are stored in an organized directory format. Thus, the file searching is easier to be performed.

At this stage, the end node files can be simplified independently. This step is taken by modifying the existing vertex clustering technique from Rossignac and Borrel (1993). As the mesh is already partitioned in previous stage, this input mesh does not need any further space partitioning. If simplification is done separately in every node, cracks and holes may be produced. In order to make sure that the whole input mesh looks good after joining back all of the node's simplified mesh, this portion of mesh should retain its boundary edges. Meanwhile, all the vertices inside the mesh are collapsed to an optimal vertex.

Inspired by OOCS algorithm (Lindstrom, 2000b), optimal vertex for the discarded vertices can be found by using single error metrics. In this case, the generalized quadric error metrics (Garland and Heckbert, 1998) is used to find the optimal representation vertex so that the normal, color or texture attributes of the geometry can be retained as well. This vertex clustering alike simplification operator introduces non-manifold vertices and edges. However, the quality is good enough and suitable for real-time application. Between, it is simple, robust and fast compared to other simplification operators. The nature of traversing the mesh once is practically inducing good I/O complexity. The output of this stage is a set of files with multiple resolutions for each node.

As the simplified meshes are pre-computed, hence, the framework is referred as discrete level of detail framework. This framework is chosen as it is fast, better suited for current hardware and imposes less computational time during run-time than dynamic LODs do. During the run-time phrase, the data for visible nodes are extracted from octree. Each of them is considered as active nodes and the triangle information is loaded into a dynamic data structure. The active nodes are expanded and collapsed based on viewing perception criteria.

3.3 Data Processing

PLY data file has header and follow by its vertex list, finally its face list. The file header starts with PLY and end with *END_HEADER*. Following is the general PLY file's header structure:

ply
format ascii 1.0
comment …
element vertex num_of_vertices
property float32 x
property float32 y
property float32 z
element face num_of_faces
property list uint8 int32 vertex_index
end_header

Subsequently, a vertex list, which total up has *num_of_vertices* of vertices and a triangle list, which total up has *num_of_faces* of triangles are listed. It is in indexed format. The details of the file format are enclosed in Section 3.3.1. Even this format is extremely space efficient. Nevertheless, it slows down the processing time. Therefore, this indexed triangle list have to be converted to triangle soup style even though it needs bigger storage space.

After reading in the PLY file portion by portion, the header of the PLY file is discarded as the other information is no need any longer. Only the number of vertices and number of triangles are retained. Besides, the datasets type is also recorded. Subsequently, two files are created, one storing the vertex values and another one storing the indexed indices for triangles.

To make the indexed mesh become a triangle soup mesh, external sorting is essential. External sorting is mandatory because the massive datasets cannot directly be loaded into main memory due to resource limitations. External sorting loads the portion of data, which fit into main memory, then sorts it and lastly output it to a file again. Here, merge sort is used for this purpose. Sorting the triangle indices involves the *quicksort* technique due of its advantage in sorting speed compared to other sorting algorithms. As mentioned, the data is read part by part. Therefore, merging is required to unite each sorted portions of data. The merging scheme used in this project is the two-way-merge sort.

By using the merge sort technique, firstly, sort the first indices of all the triangles. Then, each index is read sequentially. At the same time, the vertex values are read in sequentially as well. Now, dereference each triangle index to its corresponding vertex value. Because of the data is sorted in sequence, hence the dereferencing process is generally faster. Repeat these steps until all of the triangle's first indices are dereferenced.

Taking account of each face is in triangle shape, each triangle has three vertices. Thus, the merge sort and dereferencing processes are considered necessary to run three times in order to create a complete triangle soup mesh.

3.3.1 Data File Structure

PLY file is a simple and easy file format to store graphical objects, which are represented by a set of polygons. It is a common data format in scanning technology. Only one object is described in a PLY file. It is a collection of vertices, faces and

other elements such as color, surface normal, texture coordinates and so on. It is either an ASCII representation or binary version for compact storage and fast I/O processing. The PLY format is not intended to be a general scene description language, a shading language or a catch-all modeling format. Hence, it has no transformation matrices, object instantiation, modeling hierarchy or object sub-parts.

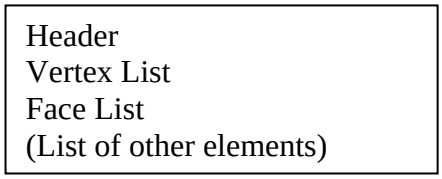


Figure 3.2 Main structure of PLY file

As mentioned before, PLY file (Figure 3.2) has a header, follow by a vertex list next, then a face list. It may has other elements that declared by users. One can ignore the unwanted information and only remain the needed data. The header includes the description of every element type, including the element's name, how many of such elements are in the object and a list of various properties associated with the element. The header also tells whether the file is ASCII format or binary format and some comments maybe. Figure 3.3 is a PLY file example.

From Figure 3.3, it illustrates the *element* is in this structure:

element <element_name> <number_in_file>

property <data_type> <property_name1>

property <data_type> <property_name1>

……

The *property* is listed in sequential order after its element. The *property* may have scalar, list and also list type. The above format is scalar type. The list type is structured as:

property list <numerical_type> <numerical_type> <property_name>

```
ply                                     --> Start with "ply"
format ascii 1.0                        --> Format=ASCII, version=1.0
comment made by tan                     --> All are comments
comment this is a cube
element vertex 8                        --> Define "vertex", 8 in this file
property float32 x                      --> Vertex has float "x" coordinate
property float32 y                      --> "y" coordinate
property float32 z                      --> "z" coordinate
element face 6                          --> Define "face", 6 in this file
property list uint8 int32 vertex_indices --> List of int vertex indices
end header                              --> Header meets its end
0 0 0                                   --> List of vertex starts
0 0 1                                       … …
0 1 1
0 1 0
1 0 0
1 0 1
1 1 1
1 1 0
4 0 1 2 3                               --> List of face starts
4 7 6 5 4                                   … …
4 0 4 5 1
4 01 5 6 2
4 0 2 6 73
4 3 7 4 0
```

Figure 3.3 PLY file example

3.4 Proposed Octree Construction

Instead of performing uniform vertex clustering, spatial octree structure is adopted in data organization. This is due to uniform clustering technique causes undesirable artifacts in the approximation even it offers great efficiency (Shaffer and Garland, 2001). Besides, it is not suitable for real-time data display. At the same time, this octree structure is vital in handling and organizing the massive datasets.

From previous data processing step, the entire processed triangle soup file is loaded portion by portion into octree structure. Octree is chosen as it eliminates the computation time spent on processing on the empty space in a data model. Before partitioning the data into octant nodes, the bounding volumes of the input object are

essential for efficiency. The information includes the width and center point of the bounding box that covers the whole mesh.

At each time, the space is divided into eight cubes recursively until the tree is fully subdivided. It partitions the input mesh adaptively. This is because it only breaks down the node into children nodes when the node has more triangles than it is allowed to. Each internal node stores their directory path, so that every node's file searching becomes easier. The leaf nodes only need to hold the filename, which is storing the partitioned triangle list.

Since the datasets could not fit into main memory, the vertices in each leaf node are written into every end node file. The file is small and is kept in an organized directory structure. Each child node is contained in their parents' node directory (previous parents' directory). Hence, the tracking of every end node file is simpler and organized better.

Different with others (Correa, 2003), this octree structure does not create any triangle replication. Whenever the triangle has existed in previous visited nodes, then the triangle would not be stored in any other node. This cause the boundary triangle is kept only once. One may question that it may create artifacts during rendering later. The artifacts occur whenever triangles inside a visible node does not be kept if it is already kept in its neighbour node. However, this artifact is rarely happened based on experiments.

By using the constructed octree as our spatial data structure, it makes simplification easier and perceptual rendering faster in general. It contains the whole world information. Every sub mesh in each leaf node is small and stored in its end node file, thus making the simplification can be performed easily. However, the octree need to be revised during simplification process if more than one level of detail is demanded.

3.5 Proposed Out-of-Core Simplification

The main flow of the simplification process has certain similarity with previous vertex clustering techniques. In many existing vertex clustering techniques, they use the idea of "triangle cluster" (Rossignac and Borrel, 1993; Low and Tan, 1997; Lindstrom, 2000a, Lindstrom and Silva, 2001), which maintain a triangle if its three vertices fall in different regions. However, this concept is not adopted here. Contrary, the boundary edges of the node are preserved. Thus, memory used to keep the list of simplified triangular mesh is nonessential anymore.

Potentially this approach avoids the problem of creating any cracks or holes after the mesh is simplified. This is because the boundary edges of every node are preserved, leaving no hole between the nodes. Hence, any patching, retriangulation or stitching (Cignoni *et al*., 2002) is unnecessary. During run-time, the simplified mesh can be loaded directly from disk. The full idea is written in following section.

How to find a representative vertex for discarded vertices inside the boundary edges? Typically edge collapse coarsening operator finds it by using a suitable metrics. Anyhow, vertex clustering alike simplification is used here. However, a vertex clustering operation is a multiple edge collapse operations. Therefore, Lindstrom (2000b) has used quadric error metrics (Garland and Heckbert, 1997) in his OOCS simplification. Inspired by this, all the vertices in a cell could be collapsed into an optimal vertex by using single error metrics.

The quadric error metrics proposed by Garland and Heckbert (1997) is robust and generate good quality simplified mesh. However, it only handles geometry data, the other surface attributes such as normal, color, texture information are not handle by this algorithm. Hence, here, the generalized quadric error metrics (Garland and Heckbert, 1998) is adapted to compute the representative vertex for the discarded vertices. It is as robust as original quadric error metrics and is able to handle the surface attributes' simplification at the same time. The complete framework is carried out in Section 3.5.2.

As the data is completely partitioned, therefore every single end node's triangle data is ready to be simplified. The process is totally independent as simplification can take place without knowing its neighbours' information. By repeating the simplification on every leaf node, it generates first level of simplification on the original input mesh. Every simplified triangular mesh is stored on disk separately. This level of detail is the finest mesh among the simplified mesh. To obtain coarser resolutions of the mesh, further simplification on internal nodes (Section 3.5.3) is required.

3.5.1 New Vertex Clustering

Vertex clustering can also be called spatial clustering as it partitions the space that the surface is embedded into simple convex 3D regions. Because triangular mesh is always represented in Cartesian coordinate system, the easiest way is to do rectilinear space partitioning or partition the space using spatial data structure such as BSP, octree, kd-tree and etc. In this project, the space is partitioned adaptively using octree because it suits the mesh's condition better. In every leaf node, the new approach on vertex clustering technique is applied to simplify the mesh. It does not need any neighbour nodes' information or any mesh stitching.

This new variation of vertex clustering technique is a fully independent simplification process. It is claimed an independent process because it does not need to know the triangles that fall into three different regions like other vertex clustering methods do. Instead, it preserves the triangles, which has the boundary edges for every node (Figure 3.4). Triangles that stay in internal area of the node are thrown away. The discarded vertices are represented by a new generated optimal vertex using the generalized quadric error metrics (Garland and Heckbert, 1998).

To find the boundary edges, every triangle in the node have to be tested its edges. Every triangle has three edges. Every edge is considered as boundary edge at starting and is stored as boundary edges. Whenever the triangle's edge is found exist in the boundary edges list, thus the edge is considered no more a boundary edge.

Else, the edge is set as boundary edge. The process keep repeated until every edge is checked. Finally, a list of boundary edges is produced. At the same time, the representative vertex is calculated. Hence, the non-degenerate triangles are produced, which every triangle consists of two vertices of a boundary edge and the representative vertex.

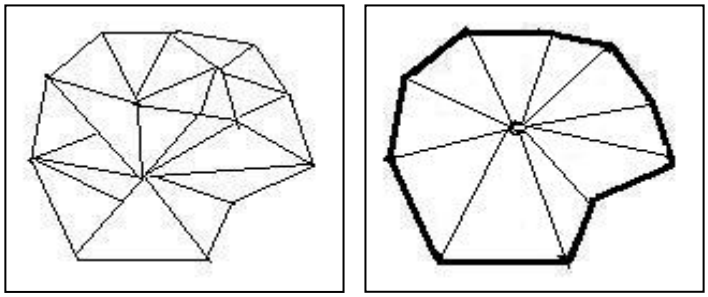


Figure 3.4 New vertex clustering

There's maybe occurrence that the substitute vertex is lie far outside from the node. The situation happens when a cell contains two nearly parallel surface sheets. Hence, the quadric may suggest a solution that is close to the intersection of both planes. Thus, the substitute vertex has to be clamped back to its cell. Here, the proposed vertex clustering technique pulls the optimal vertex to the center of the cell when it is lying too far away from cell.

3.5.2 Generalized Quadric Error Metrics

This generalized quadric (Garland and Heckbert, 1998) is improved from the original quadric error metrics (Garland and Heckbert, 1997). The original quadric error metrics only handles geometry primitives (vertex position) in mesh simplification. Although it is extended from previous quadric error metric, it cannot be generated solely by using the normal of the plane for a triangle. Instead, it needs two orthonormal unit vectors e_1 and e_2 to compute the error metrics. The unit vectors are shown in Figure 3.5.

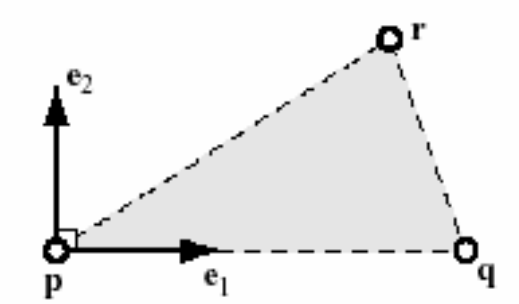


Figure 3.5 Orthonormal vector e_1 and e_2 for origin vertex p for triangle T (Garland and Heckbert, 1998)

Consider the triangle, $T = (p, q, r)$ and all properties are assumed linearly interpolated over triangles. If the vertex has color attribute, then $p = (p_x, p_y, p_z, p_r, p_g, p_b)$. If it has texture, then $p = (p_x, p_y, p_z, p_s, p_t)$. To compute e_1 and e_2, Equation 3.1 and Equation3.2 are used.

$$e_1 = \frac{q - p}{\|q - p\|} \tag{3.1}$$

$$e_2 = \frac{r - p - (e_1 \bullet (r - p))e_1}{\|r - p - (e_1 \bullet (r - p))e_1\|} \tag{3.2}$$

Squared distance D^2 of an arbitrary v from plane of T is $D^2 = v^T A v + 2b^T v + c$, which is similar to the original quadric error metrics where:

$$A = I - e_1 e_1^T - e_1 e_1^T \tag{3.3}$$

$$b = (p \bullet e_1)e_1 + (p \bullet e_2)e_2 - p \tag{3.4}$$

$$c = p \bullet p - (p \bullet e_1)^2 - (p \bullet e_2)^2 \tag{3.5}$$

A is a symmetric matrix (3x3 matrix for geometry data only; 5x5 matrix for geometry with texture coordinates data; 6x6 matrix for geometry with normal or color data), b is a vector (3-vector if is geometry data only; 5-vector for geometry with texture coordinates data; 6-vector for geometry with normal or color data), and c is a scalar (coefficients).

To obtain the optimal vertex, V_T, for a single triangle, following equation is applied:

$$AV_T = -b \tag{3.6}$$

By solving Equation 3.6, the optimal vertex with its simplified surface attributes for a triangle is computed. To simplify different types of mesh, refer Table 3.1 for each dimension it uses.

Table 3.1 Space Requirement (Garland and Heckbert, 1998)

Model type	Vertex	A	Unique coefficients
Geometry only	$[x\ y\ z]^T$	3x3	10
Geometry + 2D texture	$[x\ y\ z\ s\ t]^T$	5x5	21
Geometry + color	$[x\ y\ z\ r\ g\ b]^T$	6x6	28
Geometry + normal	$[x\ y\ z\ a\ b\ c]^T$	6x6	28

In order to get the optimal vertex for a cluster of triangles, V_N, add up all matrices A of every triangle and add up all vectors b of every triangle. For now, the solution formula becomes as Equation 3.7.

$$\sum A V_N = - \sum b \tag{3.7}$$

Solving this equation gives the representative vertex for all of the collapsed triangles in a single cell.

3.5.3 Simplification on Internal Nodes

First level of detail is generated on all leaf nodes. This is the finest simplified mesh. To get a coarser mesh, further simplification is essential to be performed on internal nodes. The process starts from root node.

Starting from the root node, its children nodes is kept checking on. The data in internal node is simplified whenever all of its children nodes are simplified in previous level. The simplification is again using the new vertex clustering technique (Section 3.5.1) and also the generalized quadric error metrics (Section 3.5.2) to obtain the substitute vertex. Thus, after the simplification done on all of the children nodes for the current node, set the node as it already been simplified. The output

triangle list is written into the current node's directory. The searching is stopped. Else, don't simplify it and the searching continues recursively.

The octree is traversed every time generating a new coarser mesh. The process is repeating until a desired number of simplified meshes are generated. As an alternative, the simplification will stop whenever the first level children nodes of the root node are simplified before.

3.6 Run Time Rendering

The rendering is based on the visibility criterion. During rendering, the boundaries of a node to the view-frustum planes are tested. If it is visible, expands the node, else, collapse it. If a node is visible, then compare the threshold based on distance aspect. If the object is far off the viewpoint, use less resolution mesh. Otherwise, the higher resolution mesh is loaded.

This process is performing the on-demand paging on the external data. The visible nodes in frustum are loaded initially. That is, load in the data from files, which generated in octree and simplification processes previously. It frees up more main memory by avoiding unnecessary data storage. From frame to frame, new visible nodes are loaded as necessary. At the same time, the loaded nodes but invisible for quite a time is thrown away from memory.

As commonly known, creation of a few resolution of mesh during the preprocess phrase is a discrete level of detail framework. Consequently, it may produce undesired popping artifacts. In order to resolve this trouble, adequate number of simplified mesh is generated. Thus, when the changes between the levels of detail switching are less, subsequently the popping problem could be minimized.

3.7 Summary

The initial framework has been proposed to carry out the out-of-core large mesh simplification with surface attributes preserved on commodity personal computer. This method is some sort of hybrid method and a new variation on previous simplification method to solve the stated issues. The implementation is explained in next chapter.

CHAPTER 4

IMPLEMENTATION

4.1 Introduction

The methodology has been revealed in previous chapter. Consequently, the details of the pseudo code and step-by-step algorithm are discussed here. As a brief review, this system involves two main processes, which are preprocessing phrase and run-time phrase. Preprocessing phrase performs data processing, octree construction and mesh simplification. Whilst run-time phrase executes the real-time rendering on simplified mesh based on the viewing criteria.

During data processing, input datasets are loaded in portion by portion. Then, external sorting and dereferencing process is carried on. In simplification process, new variation of vertex clustering algorithm is used to simplify the input mesh and a hierarchy of mesh is generated. Meanwhile, a generalized quadric error metric is used to calculate the representative vertex. This metric preserves the vertex position, normal, color and texture information after the simplification process. Then, the data is visualized subsequently.

4.2 Data Processing

4.2.1 Input Data Reading

The input file, PLY has header and list of the declared elements. It can store any polygonal information, for example storing the vertex, edge and also face list. At the same times, it can keep a lot of information such as vertex coordinates, normals, range data confidence and other different properties. Besides, the polygonal faces may in triangular shape, tetrahedral shape or rectangle shape. However, for this project, only triangular and appropriate data information is remained after the file reading. Unused data is neglected.

In this approach, the header information is not kept except the element information. The preserved elements are the “vertex” and “face” elements only. For the properties, the vertex coordinates (x, y, z), surface normals, colors and texture coordinates under the “vertex” element are retained. In no doubt, the “face” element, which consists of the number of indices for the face and list of the vertex indices, is preserved.

```
typedef struct Vertex {
  float x, y, z
} Vertex;

typedef struct NVertex {
  float x, y, z
  float nx, ny, nz
} NVertex;

typedef struct CVertex {
  float x, y, z;
  unsigned char red, green, blue
} CVertex;

typedef struct TVertex {
  float x, y, z;
  float u, v
} TVertex;
```

Figure 4.1 Data Structure for different type of vertex element

After surveying on the existing PLY files, the data type for the each of the needed elements and properties is noticed has its similarity. Figure 4.1 is the data structure used to store the data.

To read the PLY file, the pseudo code is as below:

1. Read the PLY file header and take note of number of vertices and number of triangles in this PLY model.
2. For every element,
    a. If it is “vertex”,
        i. Check the suitable data type whether it is only vertex coordinates or it has normal, color and texture coordinates.
        ii. Discard the other property (if found any).
        iii. Load in the data portion by portion, the maximum records can be loaded is depends on the allocated available main memory. Then write the data into vertex file. Repeat until all data have been written.
    b. If it is “face”,
        i. Set the data structure (as it has only one case).
        ii. Discard other property (if found any).
        iii. Load in the data portion by portion, the maximum records can be loaded is depends on the allocated available main memory. Then write the data into triangle file. Repeat until all data have been written
    c. If it is “other” element, ignore it.
3. Now the vertex file and triangle file is generated.

4.2.2 Triangle Soup Mesh Generation

Triangle soup file is mandatory to speed up the simplification and rendering process, which performs later on. Involving algorithms are the external sorting and data dereferencing processes. The concepts of two-way merge sort and data

dereferencing functions are well explained previously. At this point, the main flow of the works is described in a pseudo code chart:

1. From previous step, two files, which are vertex file and triangle file, are generated. Besides, the kind of data, whether it is vertex coordinates only or has surface normal, color or texture coordinates attributes are known. Besides, the number of vertices and number of triangle are identified. In addition, the buffer size is set. All these information is needed in this process.
2. In three passes (every triangle has three vertices),
    a. Calculate triangle's dimension and the index that will be sorted. First pass is the first index for every triangle, and so on.
    b. Externally sorts the current sorting indices.
    c. Dereference its corresponding vertex.
3. The triangle soup file is successfully generated.

4.2.2.1 Calculation of Triangle's Dimension and Sorting Index

By considering the data type for each triangle, the current record's dimension and sorting index for every pass in external sorting process can be determined. The following chart illustrates how to calculate it in three passes (Figure 4.2). The example is a data type, which only has vertex coordinates information. In first pass, the first index of a triangle is the sorting index (box in gray). Of course, the record's dimension is three as every triangle has three vertices. Now, the vertex is dereferenced into from the vertex list. Hence, first triangle's index is replaced by three corresponding vertex values, (x_1, y_1, z_1). The process is repeated for all of the first indices in the triangle list. In this calculation, the sorting index starts from zero, but not one. For every data type, the record's dimension and sorting index is listed in Table 4.1.

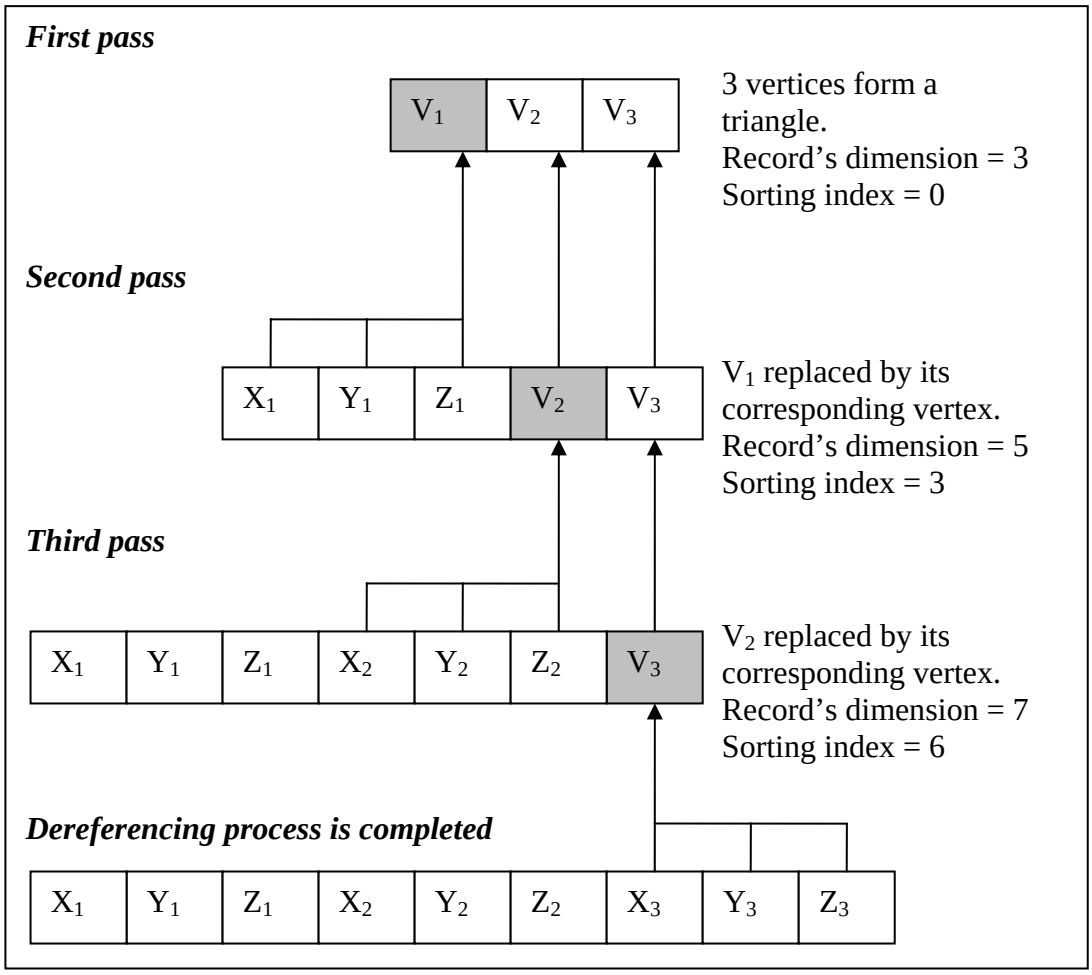


Figure 4.2 Finding record's dimension and sorting index

Table 4.1 Record's dimension and sorting index for each data type

Data type	First pass		Second pass		Third pass	
	Record's dimension	Sorting index	Record's dimension	Sorting index	Record's dimension	Sorting index
Geometry only	3	0	5	3	7	6
Geometry + normal	3	0	8	6	13	12
Geometry + color	3	0	8	6	13	12
Geometry + 2D texture	3	0	7	5	11	10

4.2.2.2 External Sorting on Sorting Indices

The sorting process is needed before the indexed indices are dereferenced. It is to speed up the data referring. Else, it may affect the I/O operation slower as the random access is a must avoided operation. By applying the sorting algorithm, the I/O operation can be done in sequence. Because the data is larger than memory size, merge sort is used to sort these massive data. *Quicksort* and two-way merge sort algorithms are applied here. The flow of the process is described as below:

1. Calculate the number of times the data loading must be performed.
   number_of_times = Dataset's size / available memory size
   // start performing sorting action
2. Load the portion of data, which is smaller than the available buffer size.
3. Perform *quicksort()* on the loaded data.
4. Output to a temporary output file.
5. Repeat step 2 – 4 for *number_of_times.*
   // start performing merging action
6. If the *number_of_generated_files* = 1, rename the file as output file.
7. Else if the *number_of_generated_files* = 2, merge the two files as output file.
8. Else (*number_of_generated_files* > 2),
    a. Divide the *number_of_generated_files* by 2, merge the pair of files
    b. If left a, odd file, rename it.
    c. Remove the unused files.
    d. Now, get the new *number_of_generated_files.*
    e. Repeats this step (step 8) until all files is merged.
9. The large data is well sorted in its current sorting index and merged into a single file.

4.2.2.3 Dereferencing on Sorting Indices

The sorted file and the vertex file are the input for dereferencing process. The following flowchart in Figure 4.3 shows its algorithm flow.

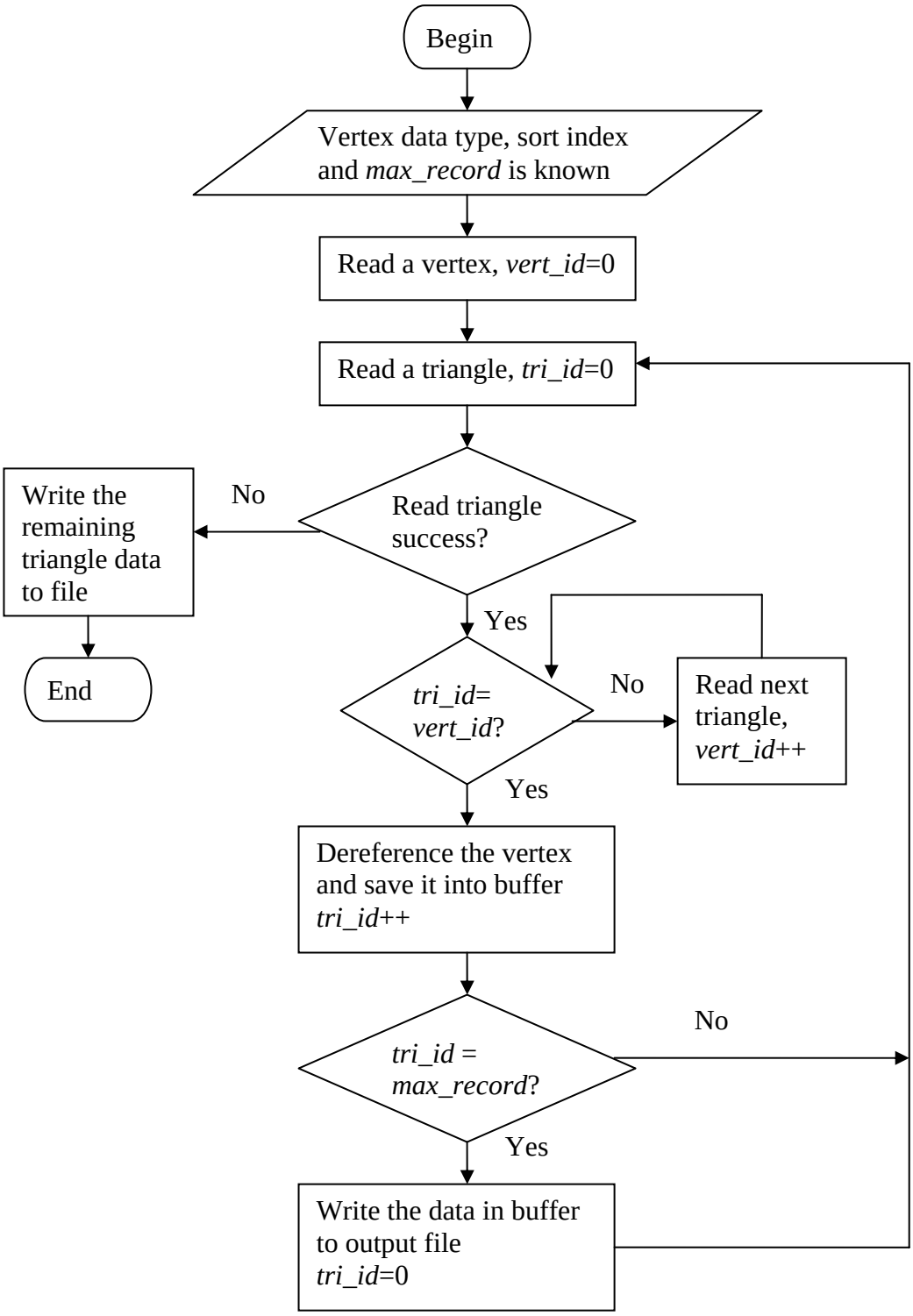


Figure 4.3 Dereferencing process

4.3 Octree Construction

The fundamental concept of octree is to partition the space into eight smaller cube recursively to become an easier handled data structure. Initially, the width and center point of the cube, which coats the whole object, must be found. Later on, the octree is built by recursively subdivide the cube. The node is subdivided into eight directions (Figure 4.4). The data members and its constraint parameters in octree class are given away in Figure 4.5.

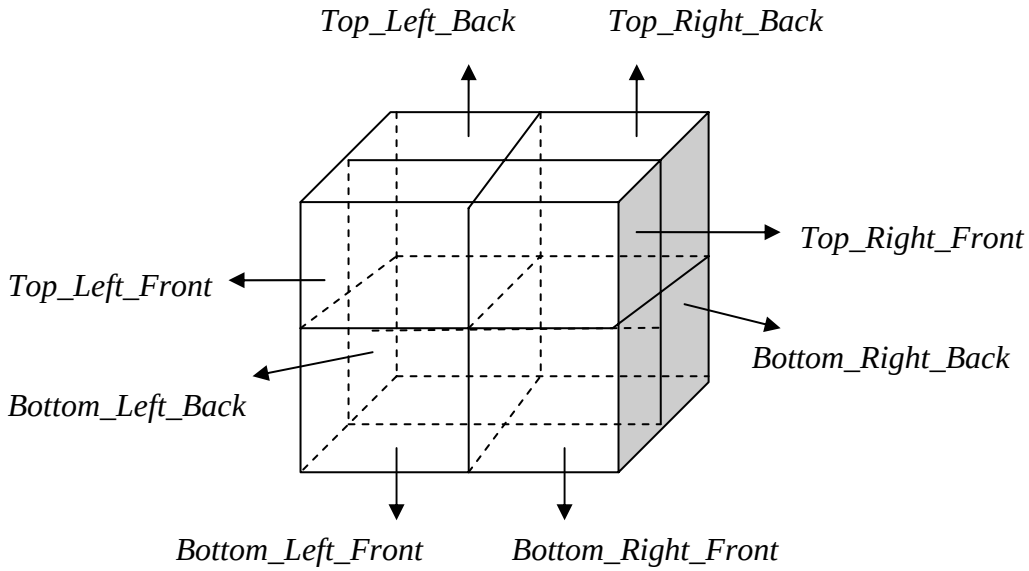


Figure 4.4 Sub nodes in an octree node

Octree class member

```
// node's information
float       width;
float       center;
bool        is_subdivided;
int         tri_count;
// node's data location
char*       nodeDirectory;
char*       endNodeFilename;
COctree*    octreeNodes[8];
// node's simplification information
bool *      is_simplified;
char*       simpFilename;
int         simp_tri_count;
```

Octree's controller parameters

```
int     max_tri
int     max_subdivision;
```

Figure 4.5 Data member and parameters in *COctree* class

The works is simplified in following pseudo code:

1. Calculate width and center point for boundary cube, *GetDimension()*.
    a. Center vertex, *center* = (total up of all the vertices' values) / total number of vertices
    b. Width, *width* is obtained by:
        i. Compute the width of *x*, *y* and *z* direction by subtracting the current width with center point.
        ii. Multiply the width by two (full width).
        iii. Compare the width in x, y and z direction. Take the greatest value as the cube width.
2. Octree generation, *CreateLargeNode()*
    a. If the *current_num_tri* > *max_tri* and *current_subdivision* < *max_subdivision*
        i. Set directory path, *nodeDirectory*.
        ii. Create eight temporary files to store triangle values for every child node.
        iii. Set the subdivision status, *is_subdivided* = true;
        iv. Load the data portion by portion which can be fit in main memory
        v. For each loaded triangle, find its location in current octree node.
        vi. Write the data into the node's file based on their location.
        vii. Repeat step (iv) to (vi) until all triangles are entirely divided.
        viii. After the mesh is fully subdivided, create eight new octree children nodes (*CreateNewLargeNode()*).
    b. Else, just rename the input file as end node file.
3. Discard all existing non-end node files. Keeping only the end node files on disk.

To create the new octree nodes (*CreateNewLargeNode()*) in previous Step 2 (viii), it is described as below:

1. Create a new child node by naming it *octreeNodes[node position]*.
2. Set node directory path, *nodeDirectory*.
3. Compute new center node and new width, *ComputeNewDimension()*.

4. Call the function *CreateLargeNode()* in Step 2 (Octree Generation) to generate an octree.

To create the new center and new width in previous Step 3 (*ComputeNewDimension()*) in creating the new octree nodes, it is describe as following:

1. Using the parents' center vertex, *center* and parents' width, *width*, the new center point for the child node is obtained.
    a. If *Top_Left_Front*, *new_center.x = center.x –width/4*
    new_center.y = center.y + width/4
    new_center.z = center.z + width/4
    b. Else if *Top_Left_Back*, *new_center.x = center.x – width/4*
    new_center.y = center.y + width/4
    new_center.z = center.z - width/4
    c. Else if *Top_Right_Back*, *new_center.x=center.x + width/4*
    new_center.y = center.y + width/4
    new_center.z = center.z - width/4
    d. Else if *Top_Right_Front*, *new_center.x=center.x + width/4*
    new_center.y = center.y + width/4
    new_center.z = center.z + width/4
    e. Else if *Bottom_Left_Front*, *new_center.x=center.x - width/4*
    new_center.y = center.y - width/4
    new_center.z = center.z + width/4
    f. Else if *Bottom_Left_Back*, *new_center.x=center.x - width/4*
    new_center.y = center.y - width/4
    new_center.z = center.z - width/4
    g. Else if *Bottom_Right_Back*, *new_center.x=center.x +- width/4*
    new_center.y = center.y - width/4
    new_center.z = center.z - width/4
    h. Else if *Bottom_Right_Front*, *new_center.x=center.x + width/4*
    new_center.y = center.y - width/4
    new_center.z = center.z + width/4
2. New width for the child node, *new_width = width/2*

4.4 Out-of-Core Simplification

4.4.1 Simplification on Leaf Nodes

As the data was completely subdivided, therefore every single end node's triangle data is now ready to be simplified independently. The steps are as below:

1. Load in the data.
2. For each input triangle,
    a. Calculate triangle's quadric, Q_T and add it into node's quadric, Q_N.
    b. For each edge,
        i. If it is not stored in edge list, add it into edge list and initially set its status as a boundary edge.
        ii. Else, set the edge's status as a non-boundary edge.
3. For each edge in the edge list,
    a. If its status is a boundary edge, save it into boundary edge list.
4. Calculate node's optimal vertex, V_N using node's quadric, Q_N.
    a. If V_N is lie too far from node, set its value the center of node.
5. For each input triangle,
    a. Check every boundary edge. If the edge is a boundary edge, add it into output triangle list and set this boundary edge not a boundary edge anymore. The triangle is consisted of two vertices from the boundary edge and the calculated optimal vertex.
6. Write the output triangle list into a file, which named using the node's directory path with its level of detail indication number.

This simplification is performed on all of the leaf nodes. Therefore, first level of detail in octree subdivided mesh is generated.

4.4.2 Simplification on Internal Nodes

After obtaining the first LOD (*level-0*), higher level of detail (*level>0*) is produced by repeating the pseudo code until desired level of detail is achieved. The

simplification for every level of detail starts by examining the root node. The process is encapsulated as below:

1. Initially set the *is_simplified[level]* status as true and examining all children nodes of the current node.
    a. If all children nodes' *is_simplified [level-1]* true, get the data from all of the children nodes.
    b. Else, set node's *is_simplified [level]* status false and stop checking on other children nodes.
2. Check for *is_simplified [level]* status,
    a. If *is_simplified [level]* is true, simplify the data obtained previously using the explained simplification algorithm (Section 4.4.1), then save it to file named *level.LOD* in node's directory.
    b. Else continue check on the children nodes.

4.5 Run-Time Rendering

For each frame, only the nodes inside view frustum are being rendered. First of all, the projection matrix and model matrix are extracted from current graphics world. Hence, the clipping planes can be created. During rendering process, every bounding cube, which bound every octree node, is then checked its eight points at the corner. If the point is in frustum, load the node's triangle list into our system.

After the previous simplification has been carried out, the mesh is simplified into a few versions. Though, there are multiresolution meshes are available for the graphics rendering. To decide which resolution of the mesh to be loaded, the distance of the object to viewing point is the key in making decision on it. Whenever the object is near to view point, extract the higher resolution node mesh. Else, use the less resolution mesh for rendering.

After determining whether a node is inside or outside the frustum and also the node's level of detail, afterward the triangles inside the node is extracted from its directory. If the normal, color or texture coordinates is provided, then this attribute is

loaded with its geometric information. By using the OpenGL functions, these triangles can be drawn subsequently.

To reduce disk access and speed up the rendering, the triangles for visible nodes are kept in main memory after loading. Hence, the same data no need be obtained from disk every frame if it is inside frustum for several continuous frames. Whenever the loaded data is no longer falls in the frustum for a period of time, then the data is obsolete and thrown from main memory to make the space available for other visible nodes.

4.6 Summary

As this methodology have to deal with variety of massive datasets, hence the implementation is very critical in memory management. The memory allocation has to be handled with cares and has to be released from time to time. It is critical to avoid memory leaking problem. Anyhow, the framework has been successfully implemented to overcome the stated problems. In next chapter, the efficiency and robustness of the framework is evaluated. Hence, the results is analyzed and discussed in following chapter.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

To evaluate the proposed methodology in large data simplification with surface preservation, the Buddha model, which is larger than mostly all low cost computer's main memory is analyzed and discussed in following experiments. Buddha model has 1, 087, 716 triangles. This out-of-core simplification is run on one CPU of a 2.4GHz Pentium IV with 512MB of RAM and NVIDIA GeForce FX 5200 graphics card.

At one time, the maximum main memory assigned for data storage and processing for the experiments is restricted to 12MB of RAM only. It is to making sure almost all of the low cost personal computers nowadays can perform this system without any memory shortage and memory leaking problems. Besides, it is designed so that main memory can be allocated in rendering or any other process.

First is the analysis on octree's performance based on the octree's depth and leaf node's size. Secondly, out-of-core simplification is evaluated carefully. To compare the algorithm with other out-of-core simplification techniques, out-of-core simplification (OOCS) by Lindstrom (2000b) is preferred. Meanwhile, the accuracy of simplified mesh is measured by using Metro tool like other algorithms always do. The quality and speed of this simplification method are revealed in numerical tables. Besides, the qualities of simplified models are visually shown in images.

5.2 Octree Construction Analysis

The time spent in octree generation is generally depends on the maximum number of triangles assigned in every leaf node and also the octree subdivision level (depth). Based on the experiments (Table 5.1), it proves the parameters continuously affects how many of the total end nodes are generated. The more the leaf nodes are created, the longer the octree building time is required.

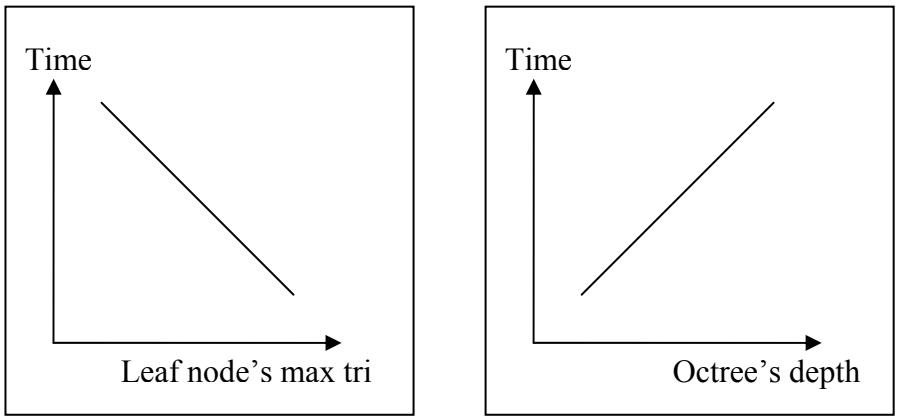
Table 5.1 Octree generation duration

Leaf nodes' max tri	Octree depth	Total of leaf nodes	Built Time (h:m:s)
1000	5	1374	6: 42 (402s)
	8	3568	8: 30 (510s)
1500	5	1316	6: 42 (402s)
	8	2380	7: 33 (453s)
2000	5	1262	6: 38 (398s)
	8	1654	6: 57 (417s)
3000	5	1127	6: 26 (386s)
	8	1140	6: 27 (387s)
6000	5	623	5: 39 (339s)
	8	623	5: 41 (641s)

Besides, one can notice that the relationships between the maximum number of triangles in leaf node (max tri) and the octree's depth with the octree building time are highly correlated (Figure 5.1). More time is imposed when the maximum triangle in every end node is less. Meanwhile, octree construction time is higher when the octree's subdivision level is higher. These two situations happen as they both are expanding the octree's size.

From the above experiments, the correlations between the parameters have illustrated that both maximum number of triangles and octree's depth are controlling the octree construction. Relationship between maximum number of triangles and octree's depth is unique. It is observed that when maximum number of triangles of leaf node is fixed, hence a deeper subdivided octree creates more end nodes and

finally enforces more octree building time (Refer Table 5.1). Similarly, when octree's depth is fixed, then the smaller node assignation will create a bigger tree. In Table 1, octrees with 3000 and 6000 maximum number of triangles have full control on the octree generation. This is mainly because both of them created tree that less the 5 level of subdivision. Hence, the assigned octree's depth has no impact on octree generation.



(a) (a)

Figure 5.1 Octree building time versus (a) maximum number of triangles and (b) octree subdivision depth

The maximum number of triangles or subdivision level shouldn't be assigned an extremely large or extremely small figure. Whenever either the maximum number of triangles or octree subdivision depth is set too high, then the other party will lose its full identity in controlling an octree construction. Let's say the octree is only allowed to be subdivided three times at most, thus setting the maximum number of triangles to a small number will only have a little impact to the octree and probably produce an unbalance tree.

5.3 Out-of-Core Simplification Analysis

In simplification analysis, some experiments in a few perspectives have been carried out. First is the analysis on the multiresolution simplified meshes, which are generated using the proposed out-of-core vertex clustering technique. Next, the

simplified models are applied in a variety of distances to show its quality based on viewing perception. Besides, this proposed simplification technique is compared with Out-of-Core Simplification (OOCS) by Lindstrom (2000b). Lastly, the relationship between simplification and octree construction is revealed.

5.3.1 Proposed Out-of-Core Simplification Analysis

From Figure 5.2, different resolutions of Buddha model, which simplified using the proposed out-of-core vertex clustering technique, are given away. The models are simplified at the first level of detail, which means each simplification is done on leaf nodes only. The quality distortion is hardly to be perceived even after a drastic simplification from 1, 087, 7106 triangles to 383, 619 triangles. The Buddha model starts obviously losing its detail when the mesh is reduced to approximate 60K polygons (Figure 5.2e).

In controlling the level of detail, the maximum number of triangles assigned to octree's leaf nodes plays an important role. That is, all of the triangles inside a node will be simplified using the new variation of vertex clustering technique with the constraint that the number of triangles it has must less than the assigned maximum number of triangles. Like in Figure 5.2a, the maximum number of triangles for node simplification is 200, thus creating a smoother looks simplified Buddha as fewer polygons are simplified once. Whilst for Buddha in Figure 5.2.e, a total of 6000 polygons are reduced to a few hundreds polygons to obtain this 60K polygon mesh. This drastic polygon reduction certainly creates poorer quality mesh.

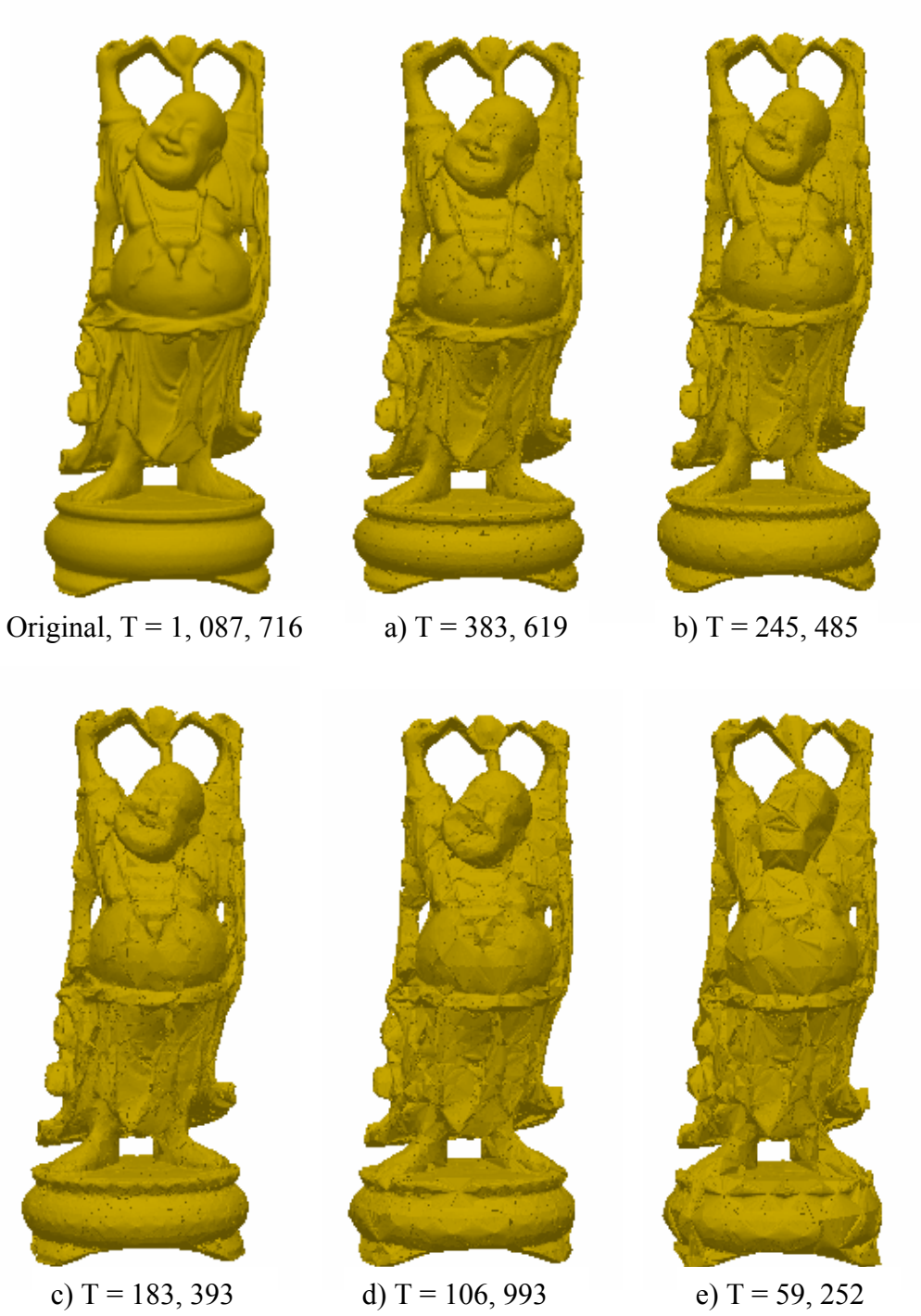


Figure 5.2 Out-of-core simplification of Buddha model in different resolutions (T = number of triangles)

To evaluate each simplification on the leaf nodes in details, the following table shows the simplification duration and the error in each simplified mesh. The mean error and RMS error are calculated using the Metro tool designed by Cignoni

et al. (1998). The coarser the mesh, the bigger the error it has. As overall, the errors are low thus the meshes' qualities are relatively good.

Investigation on Table 5.2 shows that more time is used in coarser mesh simplification. This is because, again, when the assigned maximum number of triangles is larger, thus its simplification time on each leaf nodes is higher. When the the node is bigger, the more triangles it has, thus the searching on the boundary edges are more tedious and time consuming.

Table 5.2 Simplification times and errors of simplified Buddha models

Model	T_{in}	T_{out}	Time (h: m: s)	Mean Error	RMS Error
Buddha	1, 087, 716	527, 338	55	0.000010	0.000022
Buddha	1, 087, 716	383, 619	1: 03	0.000018	0.000036
Buddha	1, 087, 716	245, 485	1: 21	0.000042	0.000073
Buddha	1, 087, 716	183, 393	2: 02	0.000070	0.000118
Buddha	1, 087, 716	106, 993	4: 51	0.000170	0.000274
Buddha	1, 087, 716	59, 252	8: 11	0.000289	0.000448

In this proposed method, the object is rendered based on the viewing distance aspect. Therefore, less detail mesh can be used when the object is far from user viewpoint as the user hardly perceives the loss of detail. Figure 5.3 shows the simplified Buddha in Figure 5.2 in different distances.

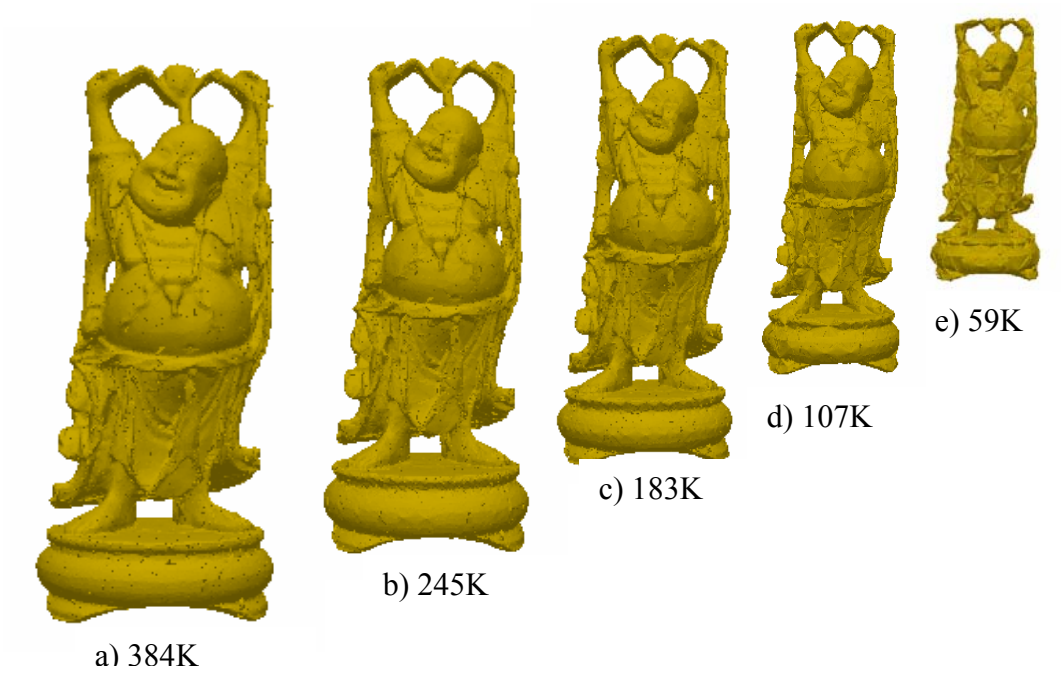
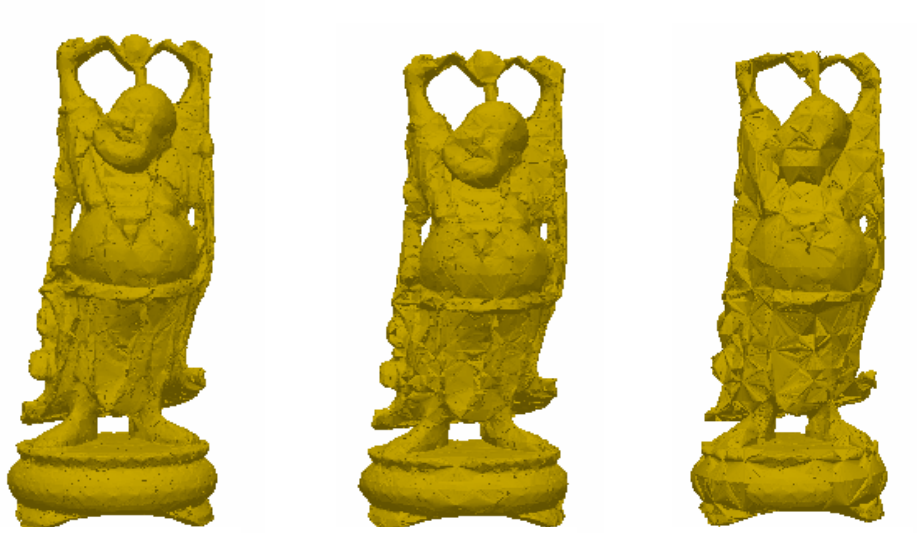


Figure 5.3 Multiresolution of Buddha model in different distances

5.3.2 Relationships between Simplification and Octree Constructions

Our out-of-core simplification is in sequence and continuous (Figure 5.4). This means the simplification on next level of detail is based on the previously simplified mesh. It is much faster than simplifying the original mesh every time a new level of detail is required as the data reading on out-of-core data is memory inefficient. Anyway, it will produce a little less quality mesh compared to the simplification directly referring to the original mesh.



LOD 1
T= 183, 393

LOD 2
T = 109, 653

LOD 3
T = 67, 435

Figure 5.4 Sequential simplification on Buddha model, using maximum number of triangles = 1000, Octree's depth = 8

The generation of first level of detail is completed by simplifying the original mesh, which already well distributed in octree leaf nodes. Whilst for the other levels of detail, it is obtained by simplifying the internal nodes of the built octree. Table 5.3 shows the generation times and output sizes of three simplified meshes. First level of detail is produced in a reasonable timing. Meanwhile, the other levels of details (LOD 2 and LOD 3) have excellent simplification durations. Subsequently, the total time for all the level of details simplification is relatively small in overall.

At the same time, Table 5.3 also demonstrates the number of triangles generated in each level of detail is about 30% to 50% of the previous simplified mesh has. The output size is depends on the octree construction setting. The smaller the maximum number of triangle assigned to the leaf nodes, the finer the mesh. For simplification on internal nodes (other levels of detail), the number of discard vertices is depends on the tree structure. Only the internal node, which has all the children nodes been simplified before is allowed to be simplified further. It ensures the simplification generally preserves the object's shape.

Table 5.3 Multiresolution simplification on Buddha in different octree structures

Octree Type	Octree Specification	Simplification level			Total time (h: m: s)
		LOD 1	LOD 2	LOD 3	
1	Max tri: 1000	Δ = 115,525	Δ = 59,252	Δ = 30,809	
	Depth: 5	T = 4: 17	T = 16	T = 18	T = 4: 51
2	Max tri: 1000	Δ = 183,393	Δ = 109,653	Δ = 67,435	
	Depth: 8	T = 2: 02	T = 13	T = 18	T = 2: 33
3	Max tri: 2000	Δ = 112,354	Δ = 59,523	Δ = 30,821	
	Depth: 5	T = 4: 27	T = 19	T = 19	T = 5: 05
4	Max tri: 2000	Δ = 127,700	Δ = 75,397	Δ = 64,353	
	Depth: 8	T = 3: 41	T = 12	T = 12	T = 4: 05
5	Max tri: 3000	Δ = 106,993	Δ = 58,726	Δ = 31,449	
	Depth: 5	T = 4: 51	T = 18	T = 18	T = 5: 27
6	Max tri: 3000	Δ = 107,691	Δ = 59,522	Δ = 36,457	
	Depth: 8	T = 4: 50	T = 19	T = 17	T = 5: 26

The simplification time and quality is directly affected by the octree structure. From the same table (Table 5.3), we can observe that the smaller the maximum number of triangle assigned to leaf node, the faster the node simplification (Figure 5.5). This is because the larger the node, the time spent for searching on boundary edges is longer.

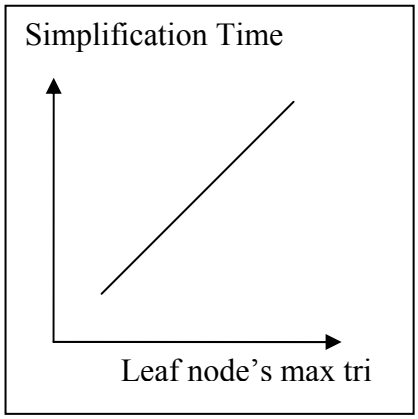


Figure 5.5 Simplification time versus leaf node's maximum number of triangles

For the same amount of maximum number of triangle, a deeper octree creates quicker simplification too. This is because when the simplification is limited to a

certain subdivision level, some nodes will be imposed a number of triangles, which is greater than the assigned maximum number of triangles. Based on the testing of octree with maximum number of triangles is 200 each node, the maximum depth of octree can reach is seven subdivision levels for the simplified mesh with 383K triangles. Meanwhile, the simplification with assigned 1000 or 2000 maximum number of triangles can reach maximum depth of six subdivision levels. Thus, when the octree's depth is limited to five levels, some nodes will be assigned a greater number of triangles than they are supposed to have. So on, the bigger node creates slower processing time as explained before. For simplification with assigned 3000 maximum number of triangles, its maximum depth is less than five levels. Hence, the simplification time and output size for both depths with level five or level eight are almost the identical.

The assignations of maximum number of triangles and octree's depth shouldn't go into extreme values. Assigning an extremely small maximum number of triangles in leaf node is discouraging. This is because very little of triangles can be eliminated in one node simplification. In the meantime, a too large maximum number of triangles also has disadvantage in introducing poor simplification.

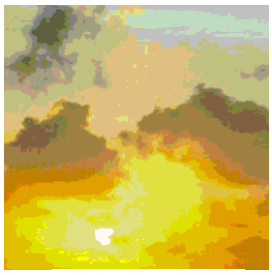
Basically an extremely low octree subdivision may create poor simplification as well. Based on the experiments, subdivision level of octree is rarely exceeding level ten. Hence, the octree won't expand too large. To control the simplification on the nodes, the best way is to set the maximum subdivision level to a relatively big number (level eight or level ten). Accordingly, the node simplification is fully controlled by the maximum number of triangles in every leaf node.

One may question when the levels of detail generation will end? It can be set to desired levels of detail. Anyway, octree's depth also plays a role in controlling the levels of detail generations. The simplification will stop when it's approaching the root node even the levels of detail generation haven't finished.

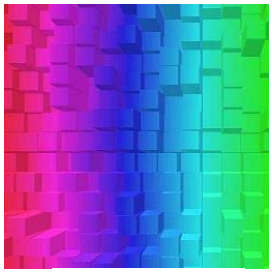
5.3.3 Surface-Preserving Simplification Analysis

The surface preservation is including attribute preservation on normal, color and texture attributes. Anyway, existing massive PLY data sets are not provided these attributes. For small PLY model with color, its RGB is all set to 255, 255, 255. Therefore, the preservation is hard to be shown. Anyway, the Generalized Quadric Error Metric (Garland and Heckbert, 1998) had proved their robustness in surface preservation.

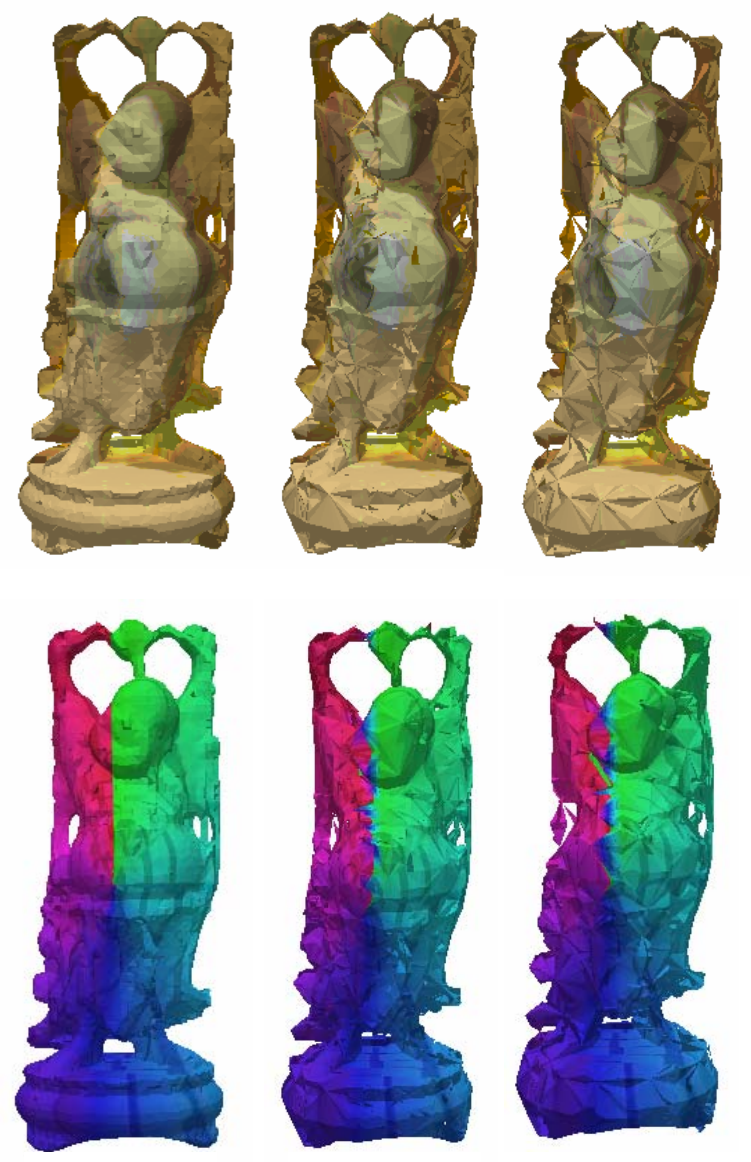
Due to the memory problem, large mesh is not able to be texture mapped. However, as a proof to attributes preservation, a simplified Buddha has been texture mapped (spherical texture mapping) using 3D modeling software (3D Max Studio) and then further simplified using the proposed algorithm. The simplification on textured object is revealed in Figure 5.6. Due to the generalized quadric error metric is assuming the mesh is continuous. Thus, we can see the discontinuous joint at the boundary of the texture.



Texture 1



Texture 2



a) 15, 536 b) 7, 997 c) 5, 484

Figure 5.6 Two different texture preserving simplifications on Buddha model

5.3.4 Comparison on Out-of-Core Simplifications

Comparison is made between our algorithm and Out-of-Core Simplification (OOCS) by Lindstrom (2000b). This is because OOCS is among the fastest simplification method and also uses the vertex clustering operator like our methodology. Moreover, the quality of OOCS technique is also good in general. Following diagram (Figure 5.7) illustrates the Buddha simplified by OOCS and our simplification algorithm. For the same amount of triangles both simplified mesh from both algorithms, OOCS uses more space partitioning than our do. Thus, OOCS produces slightly higher quality mesh than our do. In fact, fewer end nodes are used in our case yet more triangles are retained in each node because of the preservation on boundary edges.

Original Buddha

OOCS
Time = 7: 23
72 x 180 x 72 cells

Proposed method
Time = 6: 02
976 end nodes

Figure 5.7 Simplified Buddha with 90K triangles using OOCS (Lindstrom, 2000b) and the proposed method

In term of simplification time, our algorithm is faster than OOCS for a large simplified mesh (90K triangles or more). Unfortunately, for drastic simplified mesh with 50K or less triangles, the OOCS is much faster. OOCS is faster as the rectilinear cells are less. While for us, collapsing a very large node is more time

consuming because the involving boundary edges searching is longer when the node contains more triangles. Table 5.4 shows the processing time of OOCS.

Table 5.4 Simplification on Buddha model using OOCS (Lindstrom, 2000b)

Output Size ($T_{out)}$	Cell dimension	Time (h: m: s)
95340	72 x 180 x 72	7: 37
68028	57 x 150 x 57	2: 28
31564	38 x 100 x 38	57
8104	20 x 50 x 20	50

Anyhow, our simplification technique has its pros as it can overcome some other problems. First of all, simplification on single node evades unnecessary action in getting to know the neighbouring information. Moreover, the simplification on well partitioned octree nodes avoids repartitioning of mesh for more than one level of detail generations. Additionally, the simplified mesh is ready for query extraction during run-time rendering.

A big difference between OOCS and ours is, whenever several levels of detail are required, our simplification is faster by comparing the total time needed for few levels of detail generation. The scenario is explained in Section 5.2.2 previously.

Moreover, OOCS can't generate output, which its size larger than available main memory. Opposite to it, ours can do so because we are exploiting the disk usage in keeping the simplified mesh. Furthermore, the node simplification is definitely can be performed without memory shortage dilemma due to the small sub mesh is kept in every leaf node.

On the whole, the speed of our proposed method is compatible with the others as they are at least 10 times slower than OOCS do (Comparisons based on Chapter 2). These algorithms created extremely good fidelity mesh but extremely time-consuming.

5.4 Summary

From the experiments, it is proved that proposed methodology is capable in simplifying large datasets with surface preservation. An obvious finding is that octree construction greatly affects the simplification process. That is, the level of detail generation is guided by the octree structure. Letting leaf node size to control the simplification process generally can guarantee the creation of a desired output mesh. Besides, results showed that the octree subdivision level shouldn't go extremely deep to avoid extended construction time.

More experiments and brief discussion are carried out in Appendix A and Appendix B. The same testing environment is used for the experiments in appendices. Appendix A shows the results of Dragon model with 871, 414 triangles whilst Appendix B shows the results of Blade model with 1, 765, 388 triangles.

CHAPTER 6

CONCLUSIONS

6.1 Summary

This project has presented a novel out-of-core simplification with small memory allocation for computer games. In this project, the objectives of the study are

(1) To perform out-of-core simplification in low end personal computer

(2) To preserve surface attributes in simplification process

In order to make it a success mission, the methodology starts with preprocess and follows by run-time process.

The first objective is to process and simplify massive datasets so that it can be visualized during run-time. To ensure the data is loadable into limited main memory, the data is loaded part by part into main memory. Input data is converted into triangle soup representation for memory efficiency. Then, to make the data suitable for run time data accessing, the data is organized in an octree data structure, which is exploiting on disk storage. Subsequently, the mesh in every octree node is simplified independently using the proposed new vertex clustering technique. Finally, the suitable portion of mesh is extracted and rendered based on viewing perspective.

Reviewing the results in Chapter 5, it is proved that the proposed methodology is capable in simplifying the large data sets. The statistics show that the proposed simplification technique generated relatively pleasant output with small

simplification time. Small memory footprint has been exploited, as only a few megabytes of main memory are required. Anyhow, the simplification quality is constrained by octree condition and its quality could be futher improved.

In the second objective, the surface attributes are important in bringing out the beauty of an object. To do this, the generalized quadric error metrics, which formally used in vertex pair contraction has been adjusted and applied into the proposed vertex clustering technique. By using it, the best optimal vertex and the surface attributes are retained after simplification process. The metrics is robust yet easy.

As conclusion, the proposed methodology has successfully simplified and displayed massive datasets, which preserves surface attributes, such as positions, normals, colors and texture coordinates for graphics application. The invention on modifying the vertex clustering coarsening operator and adopting the suitable algorithms into this out-of-core framework has made the research goals are accomplished. This algorithm is a practical and scalable system that allows the inexpensive PCs to visualize datasets in computer games, which is formally an impossible task.

6.2 Summary of Contributions

The main research contributions are:

a) New simplification operator

The simplification technique is a new variation of vertex clustering coarsening operator. The proposed vertex clustering algorithm does not retain the triangle that fall into three different cells, but performs the simplification on single node by preserving its node's boundary. As the neighborhood of nodes is unnecessary, the node simplification is fully independent. Besides, it has made the node simplification performable in

main memory as the subdivided meshes are small enough to fit in available main memory.

b) Unique octree construction

The octree has been exploiting the file and directory system on disk in an organized scheme. By keeping the file path of every node, the node's mesh is always easy to be achieved. The children nodes are always contained in their parents' directory. Thus, in each directory, no more than eight children nodes' files are saved. This ensures the file searching is faster and systematic. The memory used to keep all the data is eliminated, thus making sure even large data also loadable into this octree structure.

Usually in octree generation, if a triangle's vertices fall into different nodes, the triangle is kept in its corresponding nodes. Subsequently, it creates replicate triangles. Here, a triangle is only being saved in one of the node that it falls. Thus, no data replication caused. The side effect of it may create artifacts during rendering is rare. This is because neighbour nodes are always fall into viewing frustum during rendering time.

c) Preserved surface attributes in large data simplification

The surface attributes are preserved by combining the generalized quadric error metrics (Garland and Heckbert, 1998) into the proposed out-of-core simplification. This metrics is originally designed for edge collapse coarsening operators. Here, the metrics is adjusted to be applicable into the proposed vertex clustering simplification operator.

In many out-of-core simplification algorithms, the surface attributes, such as normal and color are frequently preserved but not the texture attributes. Contrast to them, the texture coordinates are preserved in this proposed out-of-core simplification framework.

d) Novel out-of-core simplification

The proposed methodology so far has not been exploited by previous researches. By adopting the appropriate existing techniques and modifying some existing algorithms, it is proved that the proposed method is able to

handle the massive data simplification. In addition, the way of implementations of simplification and octree structure are significantly novel and suitable for many graphics application.

6.3 Future Work

The proposed framework showed a promising result. Nevertheless, it is not a conclusive study. In fact, improvement could be applied to this method to enhance the quality and also the speed for the simplification and rendering process. There are few possible venues for future work. First of all, the system could be improved if the main memory that an inexpensive computer has is known. That is, the maximum main memory assigned to system may not always set to a fixed value of 12MB. Instead, we can use more main memory when a higher main memory is detected on the computer. It can speed up the data processing.

Besides, there are rooms to enhance the proposed vertex clustering method. If the boundary edges could be further simplified, thus it can reduce more triangles at one time. However, caution must to be taken to avoid cracks or holes that may be generated after the simplification on boundary edges. One can adopt weighted error metric in computing the optimal vertex for the discarded vertices. This is because it generally produces better quality simplified mesh. For simplification with texture preservation, the generalized quadric error metrics could be extended to handle the discontinuous mesh.

On the other hand, try to apply other higher quality simplification operators like edge collapse to the node simplification may produce more outstanding result. To improve the quality of simplified mesh, other coarsening operators could be inserted into the current system by forming a new hybrid framework. As an opinion, one may simplify original mesh to a level of detail, which it is the highest quality mesh for the run-time rendering based on the main memory that a PC has. This avoid excessive data storage that a system may not afford to render even it is fit able into system.

From the experimental results, the optimal values for both maximum number of triangles and subdivision level in octree construction for different kind of models are found. The optimal values are found if it creates same output triangles with less computation time. However, it is more practical if the optimal values can be represented by using a formula instead of doing the try and error experiments. The formula should illustrate the relationship between the data size with the maximum number of triangles in every end node and subdivision depth.

A better real time rendering speed is desired. Due to this out-of-core framework exploits a lot of disk usage, thus the data fetching could to be improved to avoid too much of disk accessing during rendering time. For these reasons, a full prefetching technique is eagerly sought. Besides, a good geometry caching is also very welcome to be appended in this methodology.

Exploiting the OpenGL functions to fully utilities the graphics card's memory is a good idea in accelerating the rendering. Besides, changing the triangular mesh to triangle strips structure may help the rendering speed as well. In the proposed vertex clustering technique, the simplified mesh can be easily converted to triangle strips if the input mesh is a manifold mesh. Else, more works have to done to process the mesh to be manifold before hand. Besides, this methodology is looking forward to be extended to other domains, such as medical visualization or virtual geographic information system (GIS).

APPENDIX A

This appendix show results on Dragon model with some brief descriptions. Dragon has 871, 414 triangles and only has geometry data. Table A1 is the octree generation duration, which shows the octree reach does not reach depth of 5 levels when the maximum triangle in end node is 2000 triangles or more. The generation time is fast as the data is not very big.

Table A1 Octree generation duration

Leaf nodes' max tri	Octree depth	Total of leaf nodes	Built Time (h:m:s)
100	5	2159	7: 42 (462s)
	8	25733	21: 44 (1304s)
200	5	2151	6: 02 (362s)
	8	12719	15: 38 (938s)
1000	5	1958	6: 15 (375s)
	8	2463	6: 31 (391s)
2000	5	1471	5: 14 (314s)
	8	1484	5: 13 (313s)
3000	5	955	4: 42 (282s)
	8	955	4: 44 (284s)

Figure A1 shows the simplified Dragon models in a few resolutions. The model is still maintaining a good shape even simplified until 60K triangles. The simplified Dragon models in a range of distances are shown in Figure A2. To evaluate the real error of the simplified meshes, Table A2 shows that the errors are very small in overall.

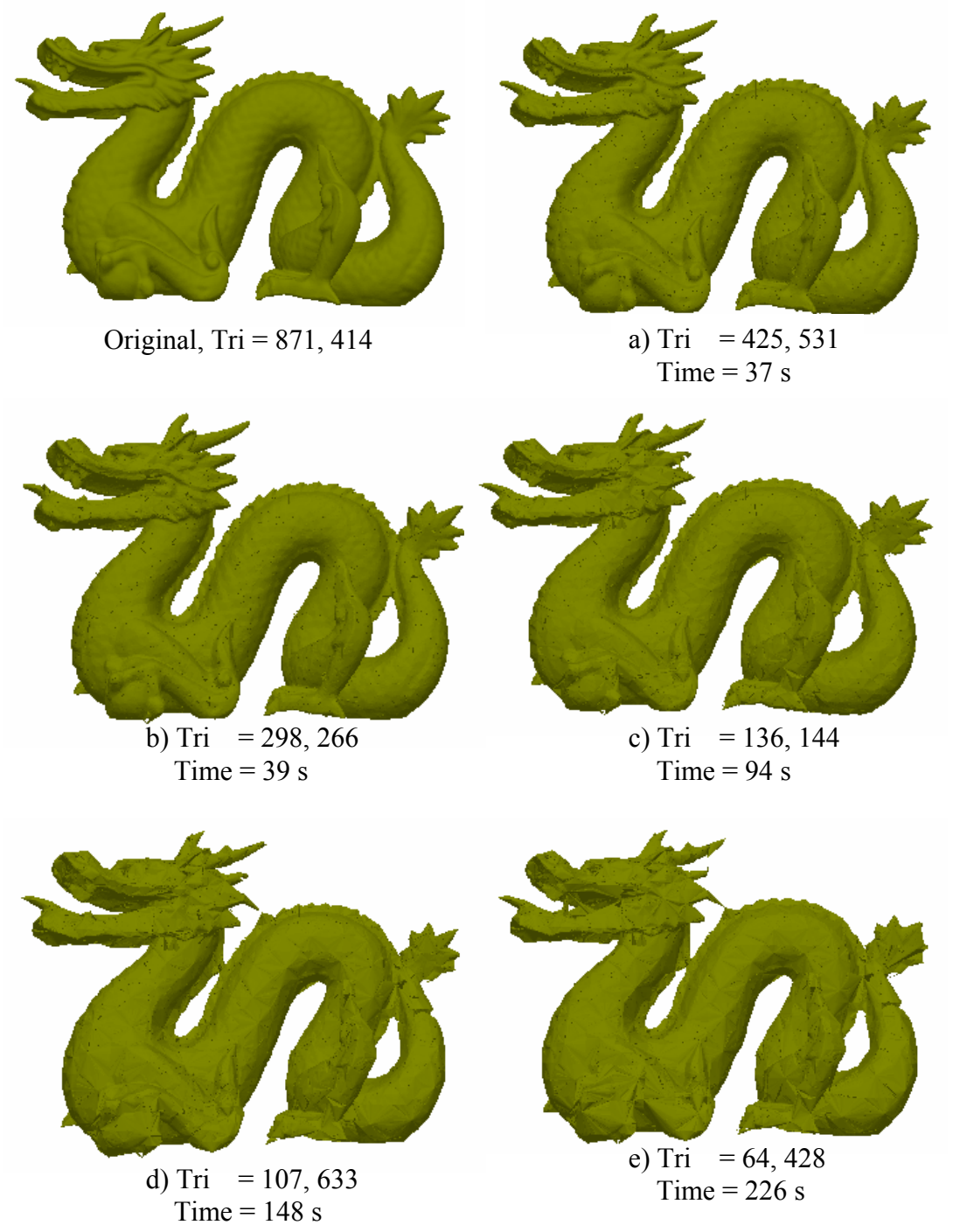


Figure A1 Out-of-core simplification of Dragon model in different resolutions (Tri = number of triangles, Time = simplification time)

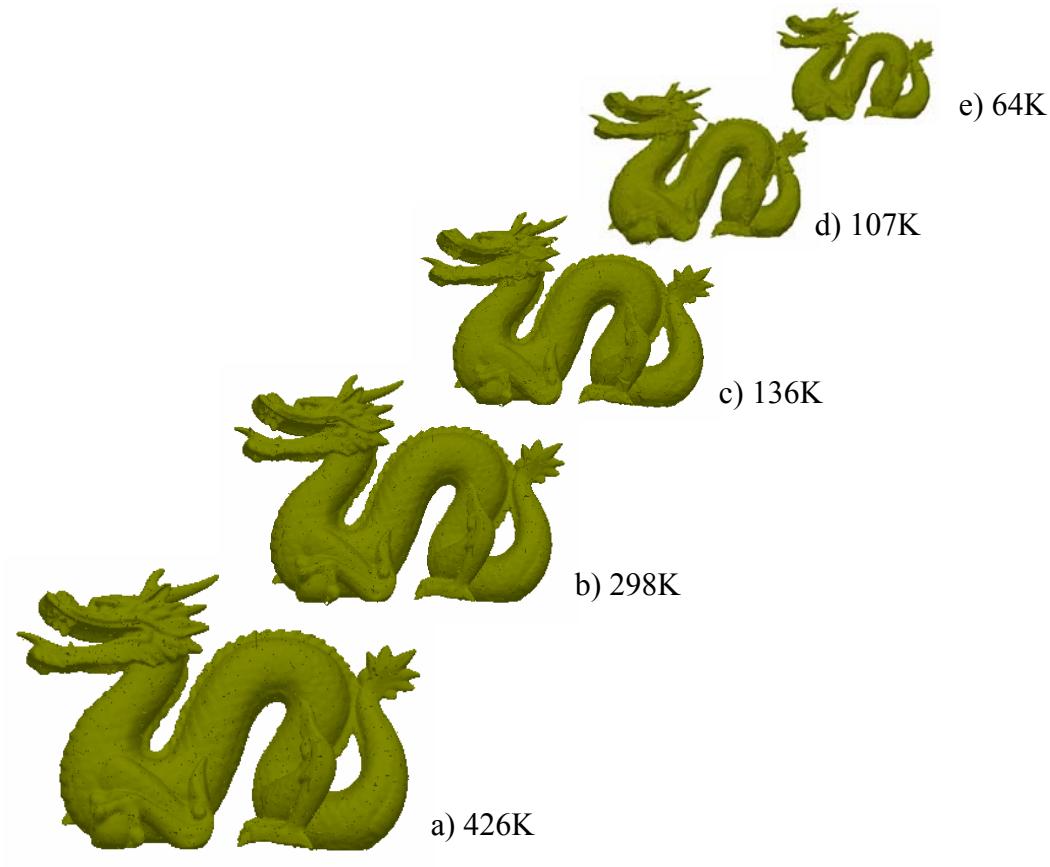


Figure A2 Multiresolution of Dragon model in different distances

Table A2 Simplification times and errors of simplified Dragon models

Model	T_{in}	T_{out}	Time (h: m: s)	Mean Error	RMS Error
Dragon	871, 414	425, 531	0: 37	0.000011	0.000022
Dragon	871, 414	298, 266	0: 39	0.000021	0.000040
Dragon	871, 414	136, 144	1: 34	0.000085	0.000140
Dragon	871, 414	107, 633	2: 28	0.000136	0.000226
Dragon	871, 414	62, 428	3: 46	0. 000198	0. 000320

A few levels of detail may be generated in an octree structure, an example of the sequential simplification is revealed in Figure A3. Besides, Table A3 shows the simplification time for different octree structures. As mentioned before, the simplification is depends on octree structure. Additionally, the octree subdivision level is not reaching level 5 when the maximum triangle in every node is 2000 triangles or more. Thus, the simplification times for octree with maximum triangles of 2000 triangles and 3000 triangles are same for depth of 5 levels and 8 levels.

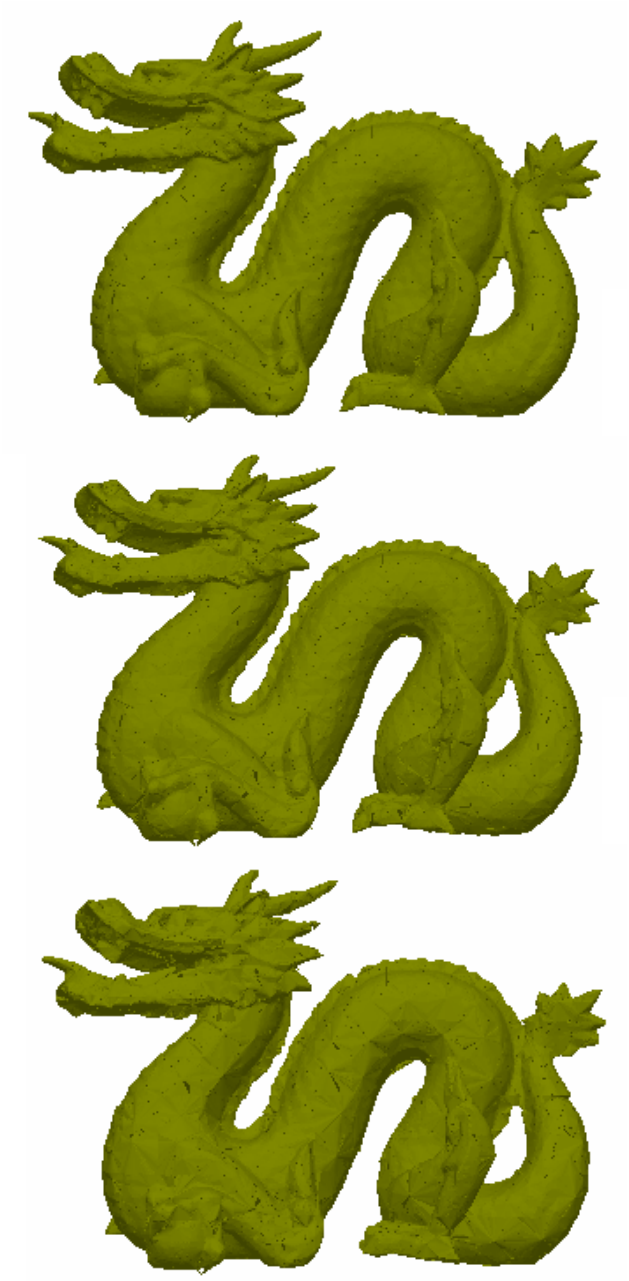


Figure A3 Sequential simplification on Dragon model, using maximum number of triangles = 200, Octree's depth = 8

Table A3 Multiresolution simplification on Dragon in different octree structures

Octree Type	Octree Specification	Simplification level			Total time (h: m: s)
		LOD 1	LOD 2	LOD 3	
1	Max tri: 100	Δ = 125,982	Δ = 65,115	Δ = 34,222	
	Depth: 5	T = 2: 55	T = 12	T = 14	T = 4: 21
2	Max tri: 100	Δ = 425,531	Δ = 245,776	Δ = 153,394	
	Depth: 8	T = 1: 04	T = 12	T = 11	T = 1: 37
3	Max tri: 200	Δ = 125,914	Δ = 65,107	Δ = 34,230	
	Depth: 5	T = 2: 37	T = 12	T = 14	T = 3: 03
4	Max tri: 200	Δ = 298,266	Δ = 179,586	Δ = 143,803	
	Depth: 8	T = 0: 39	T = 13	T = 9	T = 1: 01
5	Max tri: 1000	Δ = 122,707	Δ = 64,740	Δ = 34,404	
	Depth: 5	T = 2: 47	T = 11	T = 14	T = 4: 12
6	Max tri: 1000	Δ = 136,144	Δ = 81,320	Δ = 66,826	
	Depth: 8	T = 1: 34	T = 9	T = 9	T = 1: 52
7	Max tri: 2000	Δ = 107,249	Δ = 61,830	Δ = 35,059	
	Depth: 5	T = 3: 29	T = 10	T = 14	T = 3: 53
8	Max tri: 2000	Δ = 107,633	Δ = 62,224	Δ = 37,512	
	Depth: 8	T = 3: 28	T = 10	T = 13	T = 3: 51
7	Max tri: 3000	Δ = 87,640	Δ = 53,617	Δ = 41,303	
	Depth: 5	T = 5: 03	T = 9	T = 11	T = 5: 23
8	Max tri: 3000	Δ = 87,640	Δ = 53,617	Δ = 41,303	
	Depth: 8	T = 5: 03	T = 9	T = 11	T = 5: 23

Referring Figure A4, comparison is made between the proposed simplification method with the OOCS technique (Lindstrom, 2000b). Both simplification times are similar but the proposed method produces less quality mesh as the number of subdivided cells is less than OOCS has. Due to the object size is by default does not has the surface attributes other than geometry data and it is unloadable into 3D modeler software, thus the surface preservation is not investigated for this model.

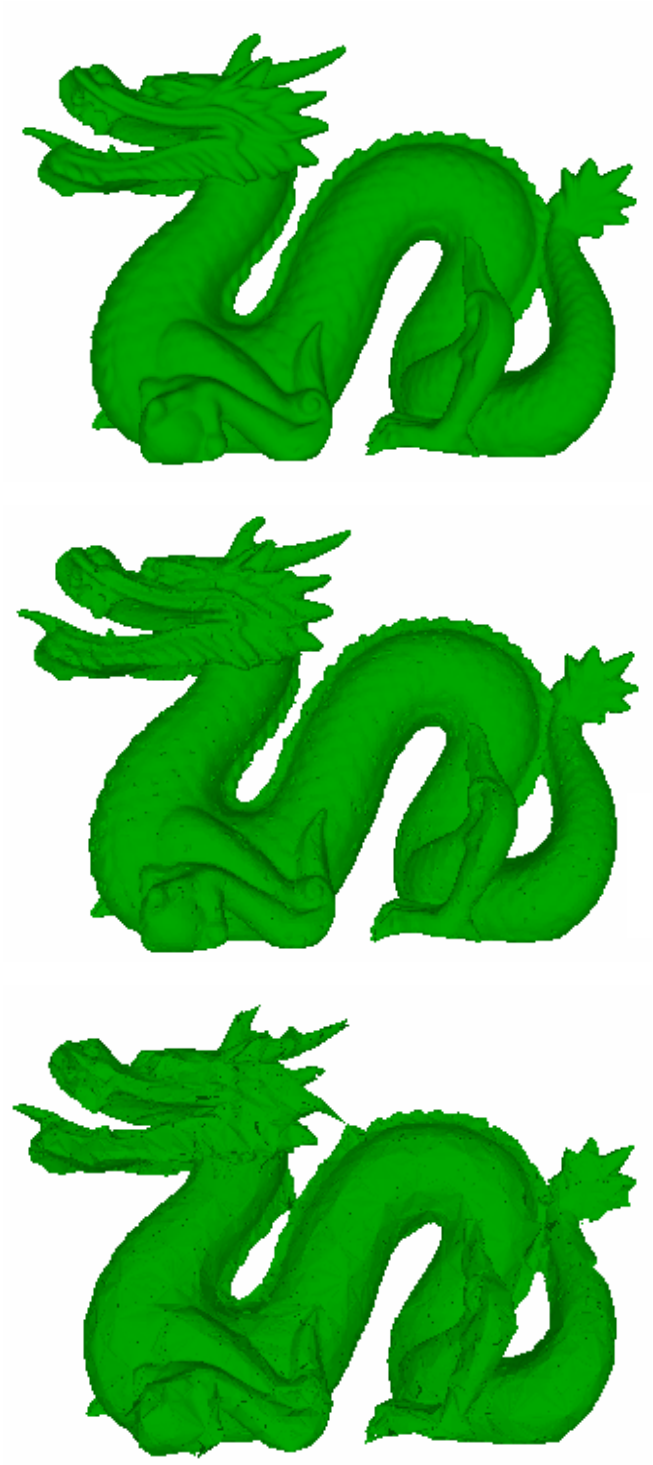


Figure A4 Simplified Dragon with 100K triangles using OOCS (Lindstrom, 2000b) and the proposed method

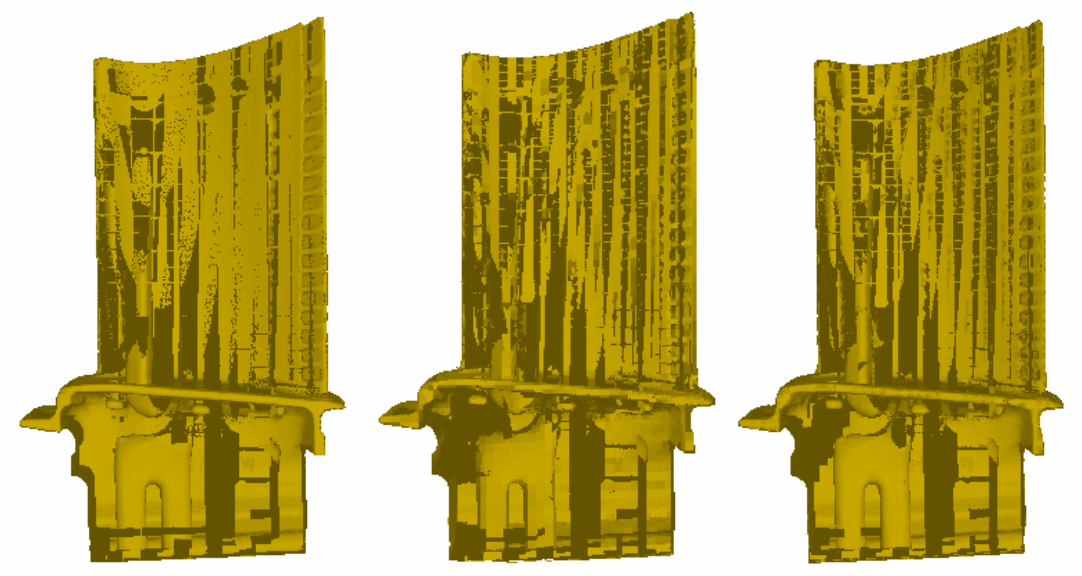
APPENDIX B

This appendix show results on Blade model with some brief descriptions. Blade model has 1, 765, 388 triangles and only has geometry data. Table B1 is the processing time of octree construction. In overall, it requires more time than other data do because the data is larger. Besides, it is noticed that the octree depth is less than 5 levels hen the maximum triangle of end node is 2000 polygons.

Table B1 Octree generation duration

Leaf nodes' max tri	Octree depth	Total of leaf nodes	Built Time (h:m:s)
500	5	2514	20: 49 (1249s)
	10	10960	29: 29 (1769s)
1000	5	2463	20: 49 (1249s)
	10	5843	20: 02 (1442s)
1500	5	2428	20: 43 (1243s)
	10	2892	21: 02 (1262s)
2000	5	2320	20: 24 (1224s)
	10	2344	20: 24 (1224s)
3000	5	2015	19: 46 (1186s)
	10	2015	19: 45 (1185s)

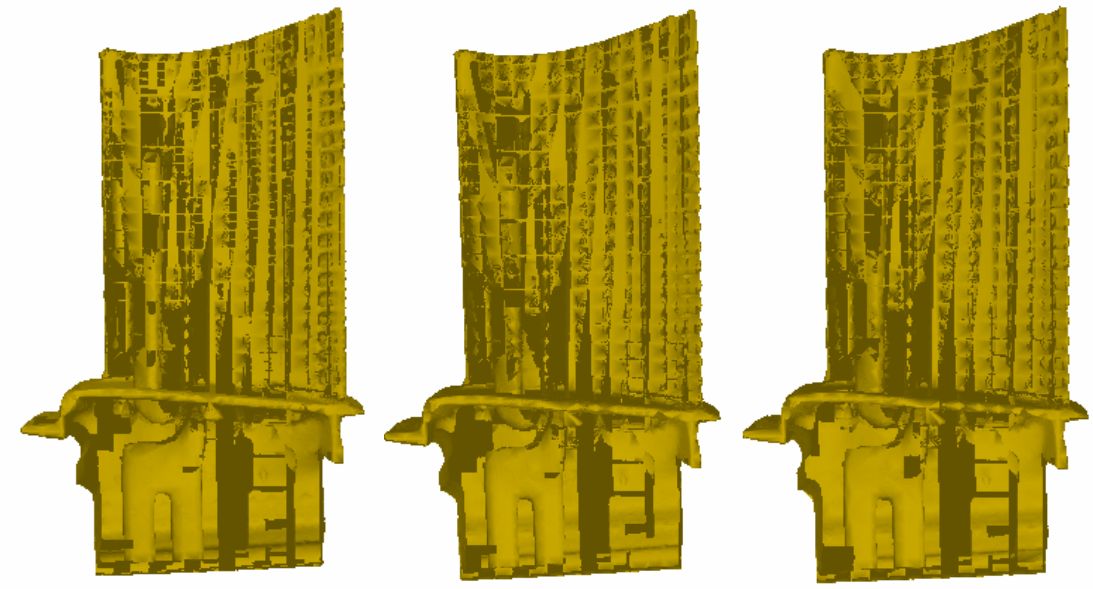
Figure B1 shows a few simplified Blade models and their simplification times. As usual, the more triangles are collapsed, the more time it needs to simplify the Blade model. The quality distortion is little as the data originally is too large. Hence, the simplified models are generally still maintaining the object's shape well. At the same time, Figure B2 is the simplified Blade models for Figure B1 in different distances.



Original, Tri = 1, 765, 388

a) Tri = 622, 868
Time = 2: 34

b) Tri = 440, 608
Time = 3: 17



c) Tri = 325, 774
Time = 5: 13

d) Tri = 247, 448
Time = 7: 30

e) Tri = 227, 934
Time = 8: 24

Figure B1 Out-of-core simplification of Blade model in different resolutions (Tri = number of triangles, Time = simplification time)

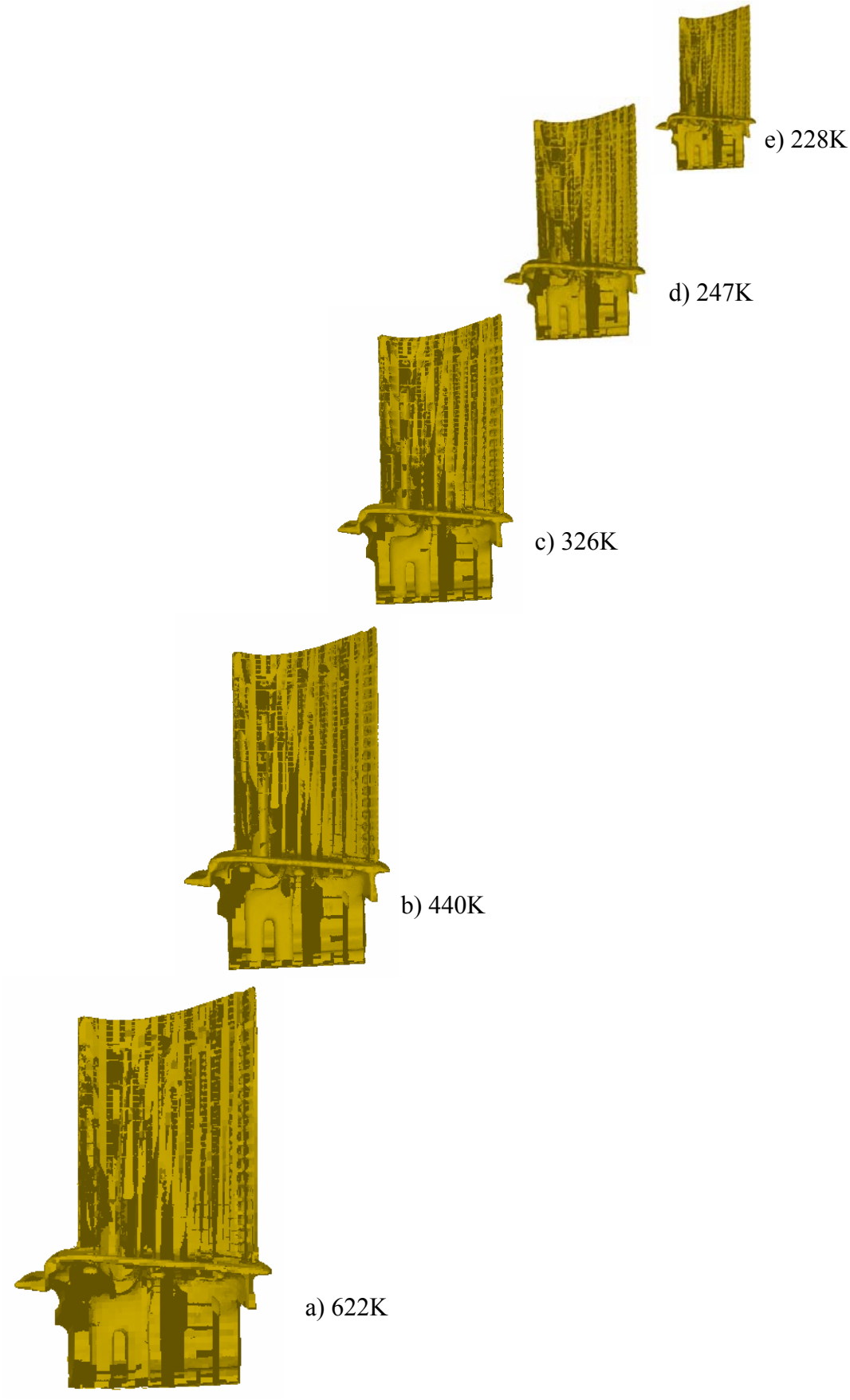


Figure B2 Multiresolution of Blade model in different distances

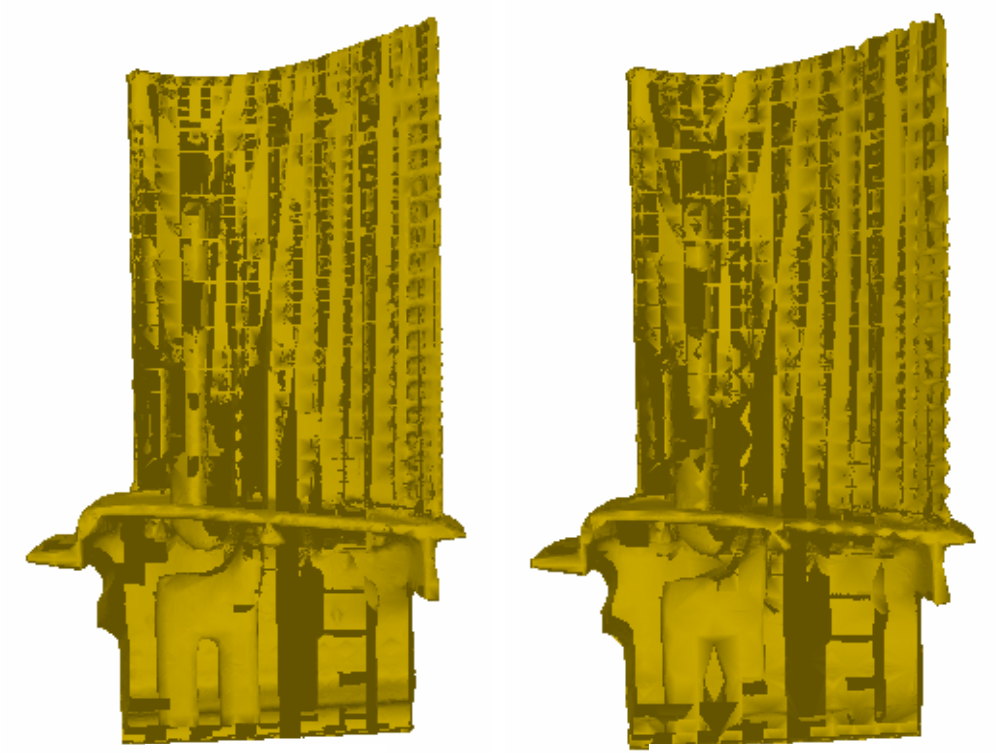
As the quality between these simplified meshes is hard to be distinguished visually, Table B2 is created to show the errors of the simplified models. The error is acceptable. For example, the error for simplified Blade with 623K triangles is relatively small.

Table B2 Out Simplification times and errors of simplified Blade models

Model	T_{in}	T_{out}	Time (h: m: s)	Mean Error	RMS Error
Blade	1, 765, 388	622, 868	2: 34	0.080685	0.195153
Blade	1, 765, 388	440, 608	3: 17	0.169567	0.345696
Blade	1, 765, 388	325, 774	5: 13	0.290001	0.526541
Blade	1, 765, 388	247, 448	7: 30	0.465160	0.764213
Blade	1, 765, 388	227, 934	8: 24	0.504452	0.816460

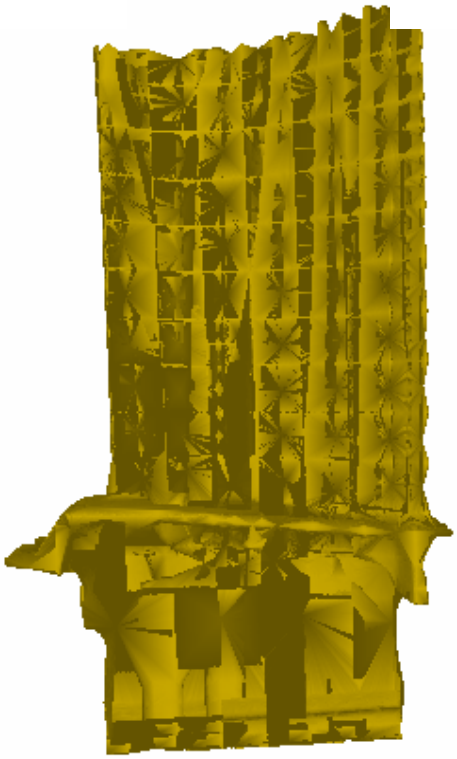
The multiresolution Blade models are simplified in a sequential way. Example of a sequential simplification is shown in Figure B3. Table B3 shows the generation of three levels of detail using different octree setting. The simplification time is less when the node size is smaller.

Referring Figure B4, comparison is made between the proposed simplification method with the OOCS technique (Lindstrom, 2000b). As mentioned previously, the simplification is limited using OOCS (Lindstrom, 2000b). Hence 100K triangles simplified meshes are compared between his algorithm with the proposed algorithm. Due to the object size is by default does not has the surface attributes other than geometry data and it is unloadable into 3D modeler software, thus the surface preservation is not investigated for this model.



LOD 1
Tri = 325,774
Time = 313 s

LOD 2
Tri = 199,734
Time = 28 s

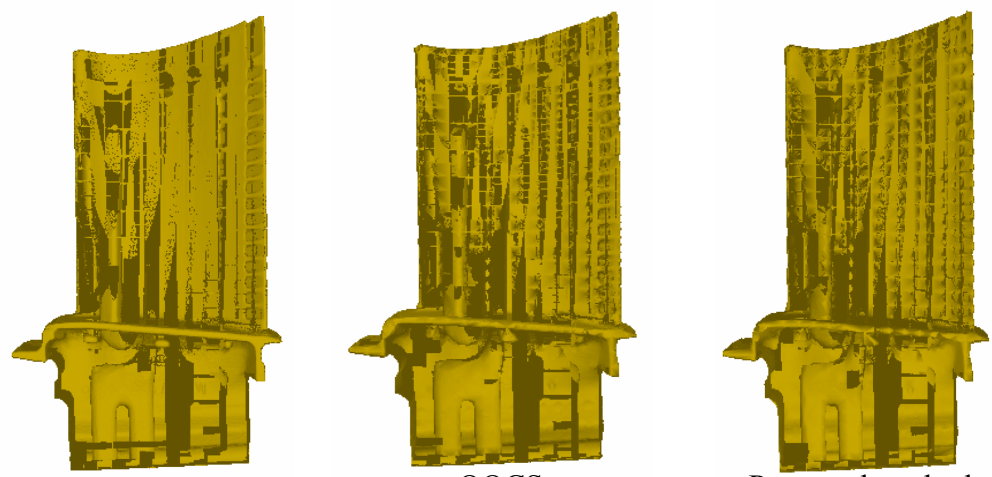


LOD 3
Tri = 132,046
Time = 38 s

Figure B3 Sequential simplification on Blade model, using maximum number of triangles = 1000, Octree's depth = 8

Table B3 Multiresolution simplification on Blade in different octree structures

Octree Type	Octree Specification	Simplification level			Total time (h: m: s)
		LOD 1	LOD 2	LOD 3	
1	Max tri: 500	Δ = 233,920	Δ = 118,864	Δ = 55,622	
	Depth: 5	T = 8: 05	T = 44	T = 54	T = 9: 43
2	Max tri: 500	Δ = 440,608	Δ = 234,106	Δ = 133,180	
	Depth: 10	T = 3: 17	T = 41	T = 46	T = 4: 44
3	Max tri: 1000	Δ = 232,780	Δ = 118,832	Δ = 55,654	
	Depth: 5	T = 8: 06	T = 43	T = 54	T = 9: 43
4	Max tri: 1000	Δ = 325,774	Δ = 199,734	Δ = 132,046	
	Depth: 10	T = 5: 13	T = 28	T = 38	T = 6: 19
5	Max tri: 1500	Δ = 231,632	Δ = 118,822	Δ = 55,654	
	Depth: 5	T = 8: 10	T = 43	T = 54	T = 9: 47
6	Max tri: 1500	Δ = 247,448	Δ = 140,646	Δ = 102,050	
	Depth: 10	T = 7: 30	T = 36	T = 44	T = 8: 50
7	Max tri: 2000	Δ = 226,904	Δ = 118,550	Δ = 55,894	
	Depth: 5	T = 8: 27	T = 42	T = 54	T = 10: 03
8	Max tri: 2000	Δ = 227,934	Δ = 120,450	Δ = 61,230	
	Depth: 10	T = 8: 24	T = 41	T = 53	T = 9: 58



Original Dragon

OOCS
Time = 9: 02
100 x 160 x 80 cells

Proposed method
Time = 8: 48
1536 end nodes

Figure B4 Simplified Blade with 100K triangles using OOCS (Lindstrom, 2000b) and the proposed method

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R & D FINAL REPORT 2nd. OPTION FORMAT

IP SCREENING & TECHNOLOGY ASSESSMENT FORM

END OF PROJECT

BENEFIT OF REPORT

BORANG PENGESAHAN LAPORAN AKHIR

TITLE PAGE (as 1st option report)

ABSTRACT(B. INGGERIS)

ABSTRAK(B. MELAYU)

ACKNOWLEDGEMENT

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UNIVERSITI TEKNOLOGI MALAYSIA
Research Management Centre

PRELIMINARY IP SCREENING & TECHNOLOGY ASSESSMENT FORM

(To be completed by Project Leader submission of Final Report to RMC or whenever IP protection arrangement is required)

1. **PROJECT TITLE IDENTIFICATION** :

OUT-OF-CORE SIMPLIFICATION WITH APPEARANCE PRESERVATION FOR COMPUTER GAME APPLICATIONS

Vote No: 75166

2. **PROJECT LEADER** :

Name : ABDULLAH BIN BADE

Address: FAKULTI SAINS KOMPUTER DAN SISTEM MAKLUMAT, UNIVERSITI TEKNOLOGI MALAYSIA, 81310 SKUDAI JOHOR

Tel : 07-5532324 Fax : 07-5565044 e-mail : abade@fsksm.utm.my

3. **DIRECT OUTPUT OF PROJECT** *(Please tick where applicable)*

Scientific Research	Applied Research	Product/Process Development
☐ Algorithm	☑ Method/Technique	☐ Product / Component
☐ Structure	☐ Demonstration / Prototype	☐ Process
☐ Data		☐ Software
☐ Other, please specify	☐ Other, please specify	☐ Other, please specify
_____	_____	_____
_____	_____	_____
_____	_____	_____

4. INTELLECTUAL PROPERTY *(Please tick where applicable)*

☑ Not patentable	☐ Technology protected by patents
☐ Patent search required	☐ Patent pending
☐ Patent search completed and clean	☐ Monograph available
☐ Invention remains confidential	☐ Inventor technology champion
☐ No publications pending	☐ Inventor team player
☐ No prior claims to the technology	☐ Industrial partner identified

5. LIST OF EQUIPMENT BOUGHT USING THIS VOT

1. Computer (HP)
2. Laser Jet Printer

6. STATEMENT OF ACCOUNT

a)	APPROVED FUNDING	RM : 28,000.00
b)	TOTAL SPENDING	RM : ……
c)	BALANCE	RM : ……

7. TECHNICAL DESCRIPTION AND PERSPECTIVE

Please tick an executive summary of the new technology product, process, etc., describing how it works. Include brief analysis that compares it with competitive technology and signals the one that it may replace. Identify potential technology user group and the strategic means for exploitation.

a) Technology Description

A 3D interactive graphics application is an extremely computational demanding paradigm, requiring the simulation and display of a virtual environment at interactive frame rates. It is significant in real time game environment. Even with the use of powerful graphics workstations, a moderately complex virtual environment can involve a vast amount of computation, inducing a noticeable lag into the system. This lag can detrimentally affect the visual effect and may therefore severely compromise the diffusion of the quality of graphics application. Therefore, a lot of techniques have been proposed to overcome the delay of the display. It includes motion prediction, fixed update rate, visibility culling, frameless rendering, Galilean antialiasing, level of detail, world subdivision or even employing parallelism. In this project, we strive to render a massive dataset in 3D real-time environment and preserve its surface appearance during simplification process using commodity personal computer. By using our out-of-core simplification technique and preserve the surface attributes on the out-of-core model based on error metrics, we can prove that our proposed methodology is capable in simplifying the large datasets with surface attributes preservation, such as positions, normals, colors and texture coordinates for graphics application. The invention on modifying the vertex clustering coarsening operator and adopting the suitable algorithms into this out-of-core framework has made the research goals are accomplished. This algorithm is a practical and scalable system that allows the inexpensive PCs to visualize datasets in computer games, which is formally an impossible task.

b) Market Potential

The output gathered from this study is useful for the industry of computer games particularly on handling and manipulating massive datasets during run-time rendering. By keeping the bulk of the data on disk and retain in main memory (or so called core) only the part of the data that's being processed, visualizing massive datasets are now possible.

c) Commercialisation Strategies

In order to commercialize this research, the prototype and technique of out-of-core simplification with appearance preservation should be promoted to the industry of computer games in Malaysia through the Development and Creative Application Center, Multimedia Development Corporation Sdn Bhd (MDC).

8. RESEARCH PERFORMANCE EVALUATION

a) FACULTY RESEARCH COORDINATOR

Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )
	Excellent	Very Good	Good	Satisfactory	Fair	Weak

Comment/Recommendations :

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…… Name : ……

Signature and stamp of JKPP Chairman

Date : ……

b) RMC EVALUATION

Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )
	Excellent	Very Good	Good	Satisfactory	Fair	Weak

Comments :-

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Recommendations :

☐ Needs further research

☐ Patent application recommended

☐ Market without patent

☐ No tangible product. Report to be filed as reference

……..

Name : …….

Signature and Stamp of Dean / Deputy Dean

Date : …….
Research Management Centre

Lampiran 20
UTM/RMC/F/0024 (1998)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN
LAPORAN AKHIR PENYELIDIKAN

TAJUK PROJEK : **OUT-OF-CORE SIMPLIFICATION WITH APPEARANCE PRESERVATION FOR COMPUTER GAME APPLICATIONS**

Saya **ABDULLAH BADE**
(HURUF BESAR)

Mengaku membenarkan Laporan Akhir Penyelidikan ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut :

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☐	TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh Organisasi/badan di mana penyelidikan dijalankan)
☑	TIDAK TERHAD	

_____
TANDATANGAN KETUA PENYELIDIK

_____
Nama & Cop Ketua Penyelidik

Tarikh : _____